Enhanced Performance Analysis of Solar Chimney Power Plant Aided with Reflectors

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Abstract

Solar Chimney Power Plant (SCPP) is guided through natural draft utilizing solar radiant energy to impart ascending thrust to the flow of air and therefore, transforming the radiant energy to run the turbine. A simplified model for a solar chimney power plant aided with reflectors is developed and a comparative study is conducted with an SCPP model without reflectors. This paper presents the enhanced performance analysis of the SCPP model with the aid of reflectors by increasing the radiant energy incident onto the floor and presents its performance for Dhahran, Saudi Arabia. For solar radiation data of 2016, the reflector aided SCPP model can produce on average, around 331kW during daytime and has an average air mass flow rate of around 432 kg/s, when compared with traditional SCPP of same geometry which produces 123kW. The energetic efficiency and power output are found to increase by 40% and 167%, respectively. Moreover, power produced, energy efficiency, the variation of temperature for the floor, the variation of mass flow rate and inlet velocity of the turbine for each month of the year are reported.

Keywords: Solar Chimney Power Plant (SCPP), Reflectors, Energy, Efficiency.

1. Introduction

SCPP is an agglomeration of three traditional mechanisms: the green house, the lengthened chimney at the center, and the wind turbine seated within the chimney. This setup fulfills the effort of transformation into electrical energy from the radiant energy of sun. This transformation involves two steps. During the first step, air flowing radially inwards under the collector transforms the radiant energy into thermal energy and this stride is fulfilled by the greenhouse effect. During the next step, the chimney transforms the developed thermal potential into kinetic energy and finally into electricity through the generator connected to the wind turbine.

In the simple model, the collector is built with the film of glass or plastic cover drawn out evenly and advanced on the top of the ground, thus the cover fulfills the objective of trapping the heated air, and in turn allows the radiation of the smaller wavelength from sun and on the other side below arresting the radiation of smaller wavelength emanated from the ground. Consequently, temperature above the ground rises up, which in turn heats the air flowing beneath the film. The elevation of the collector cover, just above the ground increases evenly towards the middle of the SCPP. This accommodates continuous smooth passage of the hot air flowing through the long tubular chimney and therefore, downsizing the disturbance within the flow and thereby diminishing the eddy loss. A flat collector of these characteristics can transform a considerable fraction of the radiant energy into thermal energy.

The idea of SCPP was conceived by (Schlaich Jorg 1995) and (Haaf et al. 1983) in the 1970s. The very first operational 36 kW pilot plant was constructed in Manzanares which is near Madrid in Spain. The concept of SCPP was developed gradually over the years, several research issues argued distinct facets of the SCPP, in which intricate mechanism of heat transfer and fluid mechanics appear. But a very few attempts have been reported to enhance the performance of the system.

One of the technique was to introduce water filled tubes for thermal storage as reported by (Kreetz, H. 1997), water filled tubes are placed on the ground upon which radiation is incident, thermal energy is stored during day time and during night time when there is no solar radiation, temperature of air in the collector drops. Then water inside the tubes releases the heat that is stored during the day. But in the extended study of (Bernardes 2004) it is reported that the power produced during the peak hours of sunshine is decreased as the heat is absorbed by the water filled tubes.

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Anyhow, uniform power output is produced throughout day and night i.e., approximately 40% of the peak power of a traditional SCPP without water tubes is produced depending upon the depth of water stored.

Later (Pasumarthi and Sherif 1997, 1998a, 1998b) developed mathematical model, performed theoretical and experimental analysis. They suggested two designs, one is to elongate the sloped collector and the other was to introduce absorber plate in between ground and glass cover, both the designs were found to enhance the energy output by 10-15% compared with previous designs. Considering the first design suggested by (Pasumarthi and Sherif 1997, 1998a, 1998b) with the increase in the elongated sloped collector would surely increase the area subjected to solar radiation, but due to geometric constraints owing to negative draft it will also increase the height of chimney which is not desirable from construction and functioning aspect of SCPP.

(Bilgen and Rheault 2005) designed sloped SCPP for hills at high latitudes and evaluated its performance. As natural hills are used as collector field, the chimney height is reduced by 90%, which reduces the construction and maintenance cost. But construction of sloped collector increases the cost as it involves much civil work. Anyhow the authors claimed the efficiency of 0.48%, which is slightly better than the traditional SCPP. (Zhou et al. 2009) proposed a novel concept for producing energy by integrating a solar collector with a man-made mountain hollow. The mountain hollow, formed by excavation in a large elevation mountain, can avoid the issues of concrete chimneys which could reduce the usage of material and construction cost.

(Islamuddin et al. 2013a, 2013b) proposed a new idea of providing an external heat source to the SCPP by placing the hollow rectangular channels beneath the collector cover and passing the exhaust gases (flue gases) through it. They developed the mathematical model and investigated the numerical simulation, they validated their result with the analytical model of (Petela 2009c). But increase in overall efficiency of the system is found to be 1.14%. Anyhow, short coming of this hybrid technique is that flue gas is to be transported to the location of SCPP or thermal power plant should be in the vicinity of SCPP.

It can be observed from the literature review that no technique is able to enhance the efficiency of SCPP by more than 1.5%. In this article, study on new technique is emphasized, keeping the geometric parameters of SCPP same as that mentioned in the literature, an effort has been made to increase the radiation incident on solar collector with the aid of reflectors. Enhancement in the performance of SCPP was observed which is described in detail by performing energy analysis for Dhahran, Saudi Arabia. The results of the current research will be a valuable reference for researchers extending their studies for enhancing the efficiency of SCPP.

2. System Description

Air enters the collector through (point 0) via a gap of H_e. The floor of the collector is of diameter D_f, which is under the transparent cover which rises proportionally to ensure a constant radial cross-section area of flow for the radially directed air. The assumption of a constant radial cross-section implies

$$\pi\, x\, D_f\, x\, H_e \;=\; \pi\, x\, D_1\, x\, H_1 \;=\; \pi\, x\, D_1^2/4 \qquad \text{(eq. 1)}$$

The values of H_e and D_f allows to determine inlet turbine diameter and height.

$$D_1 \;=\; \left(4\, xH_e\, xD_f\right)^{\frac{1}{2}} \qquad \text{(eq. 2)}$$

$$H_1 = \frac{D_1}{4} \qquad \text{(eq. 3)}$$

The Collector floor heats the air from state 0 to a state 1. Heated air expands in the turbine to state 2. The inlet and outlet diameters of the turbine are D_1 and D_2, respectively. Height of the turbine is H_T; ($H_1 + H_T = H_2$). Air after expansion leaves the SCPP through the top of chimney of height H_3. Fig. 1 depicts the schematic representation of the SCPP taken into consideration for the present study.

Tab. 1: Dimensions of SCPP considered for present study

Geometric Parameter	Dimensions in Meter
D_f (Diameter of floor surface)	240
H_3 (Height of Chimney)	195
H_e (Height of Deck at Point 0)	0.3

The above dimensions from Tab.1 are substituted in afore mentioned geometric correlations to obtain overall dimensions of SCPP, owing to the fact to keep constant radial cross sectional area throughout the flow.

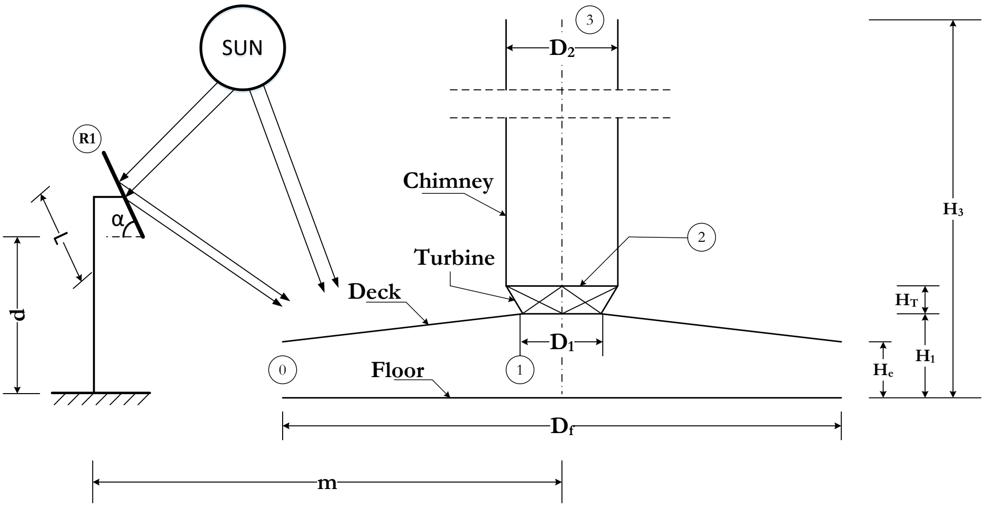


Fig. 1: Schematic Diagram of Solar Chimney aided with reflector

Once the geometric parameters of SCPP are determined then the location of reflectors is set such that the radiation incident on the mirror is reflected on to the collector field. Here, m denotes the distance of mirror from the center of SCPP, d, denotes the height between lower edges of mirror to the ground, L, denotes the length of mirror placed at an angle α. Since the mirrors are placed around the deck in concentric pattern, in our analysis, we consider the location of mirror along the mean position of the mirror field.

The ratio of reflection of mirror on deck to each mirror area is assumed to be one, which implies total area of mirrors required is equal to area of deck.

$$Number\ of\ mirrors = \frac{Total\ area\ of\ deck}{Area\ of\ each\ mirror} \qquad \text{(eq. 4)}$$

The dimensions of SCPP and positioning of mirror with respect to SCPP evaluated in this study are provided in Tab.2.

Tab. 2: The dimensions of the SCPP aided with reflectors under evaluation

Geometric Parameter	Dimensions
Area of each mirror	4 m2
Number of mirrors	11260
m	150 m
L	2 m
d	10 m
Alpha	70^0

3. Mathematical Modeling

First geometric modelling of SCPP is performed which is followed by energy analysis of the SCPP. The thermodynamic equations are derived by obtaining the correlation between the solar input energy, energy losses at various locations, and final output power. Then, it is followed by analyzing SCPP model for Dhahran conditions depending up on the solar irradiation data. Once all the correlations between energy input and final output are obtained, all the equations are solved simultaneously using EES.

3.1. Energy Analysis

Energy conservation principle using control volume approach is applied to each part of the SCPP. The energies are represented by E and the six energy balance equations are used considering the floor surface, collector (includes floor, air and deck), turbine, air in collector, chimney as presented by (Hussain and Al-Sulaiman 2016).

$$E_{s-f} + S_R = E_{f-a} + E_{f-d} \qquad \text{(eq. 5)}$$

$$E_{f-a} + E_{d-a} = E_{a1} + E_{w1} + E_{p1} \qquad \text{(eq. 6)}$$

$$E_{S-f} = E_{a1} + E_{w1} + E_{p1} + E_{d-sky} + E_{d-amb} + E_{d-ch} \qquad \text{(eq. 7)}$$

$$E_{a1} + E_{w1} + E_{p1} = E_{a2} + E_{w2} + E_{p2} + E_{Power} \qquad \text{(eq. 8)}$$

$$\begin{aligned} E_{a2} + E_{w2} + E_{p2} + E_{d-ch} = {} & E_{a3} + E_{w3} + E_{p3} \\ & + E_{ch-amb} + E_{ch-sky} + E_{ch-gr} \qquad \text{(eq. 9)} \end{aligned}$$

$$E_{a-ch} + E_{d-ch} = E_{ch-amb} + E_{ch-sky} + E_{ch-gr} \qquad \text{(eq. 10)}$$

Subscripts used in the above equations have the following definitions:

Tab. 3: Definition of subscripts in the above equations (5)-(10).

Subscript	Definition	Subscript	Definition
S-f	The solar radiation reaching the floor.	S_R	Radiant energy obtained by reflectors.
f-a	Heat transfer by convection from floor to air. .	ch-sky	Heat transfer by radiation from chimney to sky.
f-d	Heat transfer by radiation from floor to deck.	ch-gr	Heat transfer by radiation from chimney to ground.
d-a	Heat transfer by convection from deck to air.	a-ch	Heat transferred from the air in chimney to the surface of chimney.
d-ch	Heat transfer by radiation from deck to chimney.	a1, a2, a3	Enthalpy of air at different points.
d-sky	Heat transfer by radiation from deck to sky.	w1,w2, w3	Kinetic energy of air at different points.
d-amb	Heat transfer by convection from deck to atmosphere.	p1, p2, p3	Potential energy of air at different points.
ch-amb	Heat transfer by convection from chimney to atmosphere.	P	Power generated by turbine.

The Kinetic energies are calculated using the well-known formula:

$$E_w = m \times w^2/2 \qquad \text{(eq. 11)}$$

The mass flow rate m is calculated as:

$$m = 0.25 \times \pi \times D_1^2 \times w_1 \times \rho_{a1} \qquad \text{(eq. 12)}$$

Where, w represents velocity and ρ represents density.

Enthalpy of air is calculated using the formula:

$$E_a = m \times c_p \times (T_a - T_0) \qquad \text{(eq. 13)}$$

The potential energies of air are calculated using the formula derived by (Petela 2009b):

$$E_p = m\left\{-\frac{1}{\rho}\left[\frac{b}{6d}(\rho - e)^3 + \frac{a}{2}(\rho - e)^2\right]\right\} \qquad \text{(eq. 14)}$$

Where, a, b, d and e are constants having a particular value, given by (Petela 1964, 2003, 2008a, 2008b, 2009a).

The solar energy received by the floor of the collector is given as:

$$E_{S-f} = \tau_d \varepsilon_f I A_d \qquad \text{(eq. 15)}$$

Where, I is the incident solar radiation on the earth surface, τ_d is the transmissivity of deck, and ε_f is the emissivity of the collector floor, A_d is the floor surface area, which receives the solar radiation and defined as:

$$A_d = \pi(D_f^2 - D_1^2)/4 \qquad \text{(eq. 16)}$$

The additional solar energy S_R received by the floor with the aid of reflectors is defined as:

$$S_R = r_1 \tau_d \varepsilon_d I A_d \qquad \text{(eq. 17)}$$

Where r_1 represents the reflectance of reflector R1, and was assumed to be 0.9, τ_d is the transmissivity of deck, and ε_f is the emissivity of the collector floor reflectors are assumed to be of same area as of floor surface area.

The energy radiated by the deck to chimney is calculated as:

$$E_{d-ch} = \varepsilon_d \frac{\pi}{4}\left[D_f^2 - (c_D D_2)^2\right]\sigma(T_{dE}^4 - T_{ch}^4) \qquad \text{(eq. 18)}$$

T_{dE} is the effective temperature of the deck, c_D is factor which is used to account for the thickness of the chimney wall. The shape factor for radiation from the deck to the chimney ϕ_{d-ch} can be calculated as:

$$\phi_{d-ch} \frac{\pi}{4}\left[D_f^2 - (c_D D_2)^2\right] = \phi_{ch-d} \pi c_D D_2 (H_3 - H_2) \qquad \text{(eq. 19)}$$

Where, ϕ_{ch-d}can be determined from

$\phi_{ch-d} = 0.5 \times (90 - \beta)/90$, the value for β is found from $\tan\beta = 2 \times H_3/D_f$

Energy radiated from the floor to the deck is given by:

$$E_{f-d} = A_d \sigma(T_{fE}^4 - T_{dE}^4) \qquad \text{(eq. 20)}$$

Where, T_{fE} is the effective temperature of the floor.

Energy transfer from the floor to air by convection is given as:

$$E_{f-a} = A_d h_{f-a}(T_{fE} - T_{aE}) \qquad \text{(eq. 21)}$$

Energy transfer from the deck to air by convection is given as:

$$E_{d-a} = A_d h_{d-a}(T_{dE} - T_{aE}) \qquad \text{(eq. 22)}$$

Energy transfer from the deck to ambient by convection is given as:

$$E_{d-amb} = A_d h_{d-amb}(T_{dE} - T_{amb}) \qquad \text{(eq. 23)}$$

Energy transfer from the chimney to environment by convection is given as:

$$E_{ch-amb} = A_{ch} h_{ch-amb}(T_{ch} - T_{amb}) \qquad \text{(eq. 24)}$$

Energy transfer from air inside the chimney to the chimney wall by convection is given as:

$$E_{a-ch} = \pi D_2 (H_3 - H_2) h_{a-ch}\left(\frac{T_{a2}+T_{a3}}{2} - T_{ch}\right) \qquad \text{(eq. 25)}$$

In the above equations h is the convective heat transfer coefficient for the respective pair of the surfaces, and the chimney surface area is defined as:

$$A_{ch} = \pi \times c_D \times D_2 \times (H_3 - H_2) \qquad \text{(eq. 26)}$$

The convective heat transfer coefficient h_{a-ch} can be determined as, $h_{a-ch} = Nu \times k/D_2$. The Nusselt number is calculated from $Nu = 0.023 \times Re^{0.8} \times Pr^{0.4}$. Here Reynolds number is calculated as $Re = w_2 D_2/\nu$, and the Prandtl number (Pr) is taken as constant for air, Pr=0.7.The convective heat transfer coefficient h_{f-a} is determined considering forced convection. The calculations for h_{f-a} is made using Reynold's Number, instead of Grashoff Number. For this the average flow velocity of the air is assumed. Energy radiated from the deck to the chimney is given as:

$$E_{d-ch} = \phi_{d-ch} A_d \sigma (T_{dE}^4 - T_{ch}^4) \quad \text{(eq. 27)}$$

Energy radiated from the deck to sky is given as:

$$E_{d-sky} = \phi_{d-sky} A_d \sigma (T_{dE}^4 - T_{sky}^4) \quad \text{(eq. 28)}$$

Energy radiated from the chimney to sky is given as:

$$E_{ch-sky} = \phi_{ch-sky} A_{ch} \sigma (T_{ch}^4 - T_{sky}^4) \quad \text{(eq. 29)}$$

Energy radiated from the chimney to the ground which is not a part of the collector is given as:

$$E_{ch-gr} = \phi_{ch-gr} A_{ch} \sigma (T_{ch}^4 - T_{gr}^4) \quad \text{(eq. 30)}$$

The shape factor relations are as follows:

$$\phi_{d-sky} + \phi_{d-ch} = 1 \quad \text{(eq. 31)}$$

$$\phi_{ch-sky} + \phi_{ch-d} + \phi_{ch-gr} = 1 \quad \text{(eq. 32)}$$

Where, $\phi_{ch-sky} = 0.5$.

Temperature T_{a2} is calculated using the equation for isentropic expansion in turbine, which is defined as

$$\frac{T_{a2}}{T_{a1}} = \left(\frac{p_2}{p_1}\right)^{\frac{\kappa}{\kappa-1}} \quad \text{(eq. 33)}$$

Where κ for air is 1.4. Internal efficiency of turbine is η_T. Energy is converted into electric power at an overall efficiency η_0, which also includes mechanical and electrical efficiencies of the turbine generator. Further as mentioned in (Petela 2009b, 2009c), the temperature drop in the chimney can be estimated using eq. 34.

$$T_{a2} - T_{a3} = 0.154 \times D_2 \times H_3 / m \quad \text{(eq. 34)}$$

Air distribution inside the collector was assumed to be linear. Therefore, the average temperature of air inside the collector was calculated as:

$$T_{aE} = (T_{amb} + T_{a1})/2 \quad \text{(eq. 35)}$$

Relative pressure drop across the chimney for maximum fluid power was given by (Backstrom and Fluri 2006) as:

$$\frac{P_1 - P_2}{P_1 - P_3} = \frac{2}{3} \quad \text{(eq. 36)}$$

The energetic efficiency of an SCPP aided with reflectors is described as below.

$$\eta_{energy} = \frac{E_{power}}{E_{sf} + S_R} * 100 \quad \text{(eq. 37)}$$

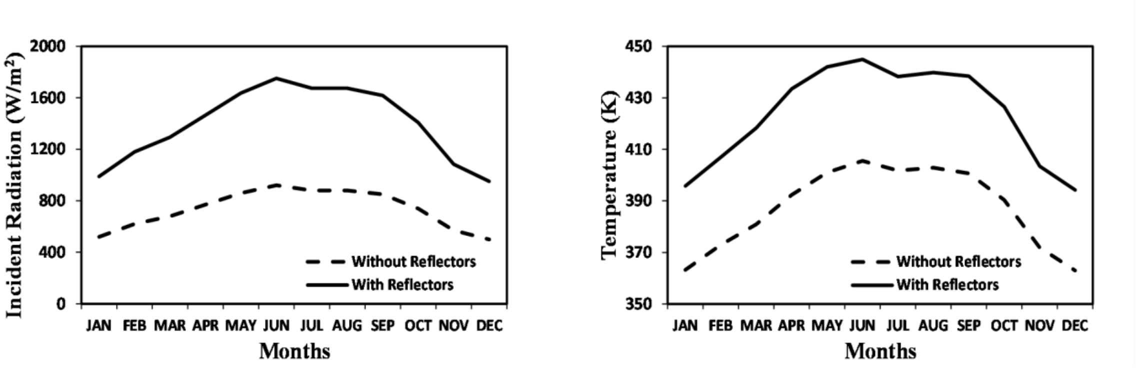
The following assumptions are used:

$T_{gr} = T_{amb}$, $c_D = 1.015$, $c_p = 1000 \frac{J}{kg} K$, $\kappa = 1.4$, $\eta_T = 0.7$, $H_T = 1\,m$, $h_{ch-amb} = 7 \frac{W}{m^2} K$, $h_{d-amb} = 5 \frac{W}{m^2} K$, $H_0 = 0.3\,m$

4. Results and Discussion

All the above formulated energy equations have been solved using sufficient and necessary assumptions with the help of EES software simultaneously, considering all the losses into account which eased in determining the theoretical final power output and hence forth the theoretical efficiency as well. Taking monthly average data into consideration, energy output and efficiency were determined for the SCPP model with and without reflectors for Dhahran, Saudi Arabia. The direct relationship between the energy output and the efficiency could not be drawn as they are dependent on many inter-dependent parameters, such as solar insolation, wind speed, atmospheric temperature. Furthermore, the geometry of the solar chimney model plays a vital role, which was clearly depicted in the results below. All the required data such as average insolation, wind speed, and atmospheric temperature for Dhahran, Saudi Arabia, was taken from NASA metrological website for the year 2016 which has a record of data for past 22 years.

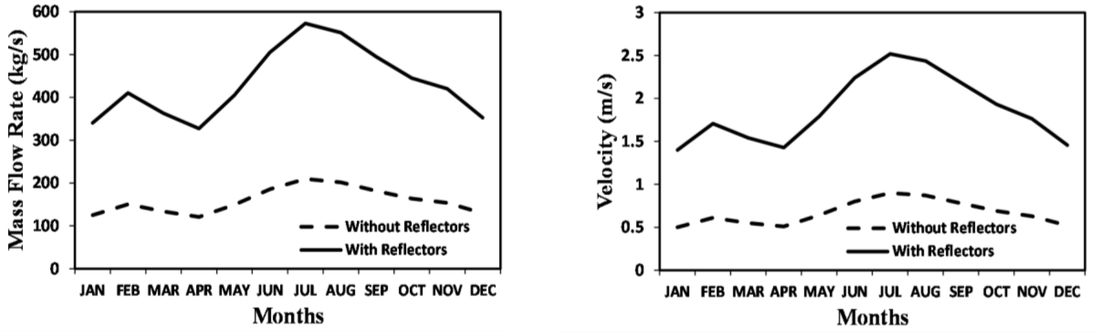
From Fig. 2(a). With the aid of reflectors it is evident that there was increase in amount of irradiation incident on collector surface area by 90.25%, maximum intensity is found during the summer months vice versa along the winter months it is found to be minimum. It followed the same pattern as that of the available solar radiation over a period of one year. Fig. 2(b). Depicts the temperature of the floor upon which solar radiation is incident. The average ambient temperature for Dhahran is 297K, average floor temperature for SCPP model with and without reflectors are found to be 423K and 387K. Increase in floor surface temperature when aided with reflectors is found to be 9.3%, the higher floor temperature causes the density variation in air which in turn moves air towards the center i.e., low density area which helps in driving the turbine. The maximum temperatures were found to be for the summer months, which also correspond to maximum power generated. Across the winter months the temperatures were observed to be lower which corresponds to a lower power output as well.



2 (a) **2 (b)**

Fig. 2: (a) Variation of incident radiation on SCPP model at Dhahran, Saudi Arabia. (b) Variation of floor temperature.

Variation of Mass flow rate and velocity at the inlet of the turbine are summarized in Fig. 3. The highest velocity and greater mass flow rate are observed for the month of July and August which has the highest incident solar radiation, as well as, higher energy output. With the aid of reflectors, average increase in velocity and mass flow rate are found to be 180% and 172% respectively.

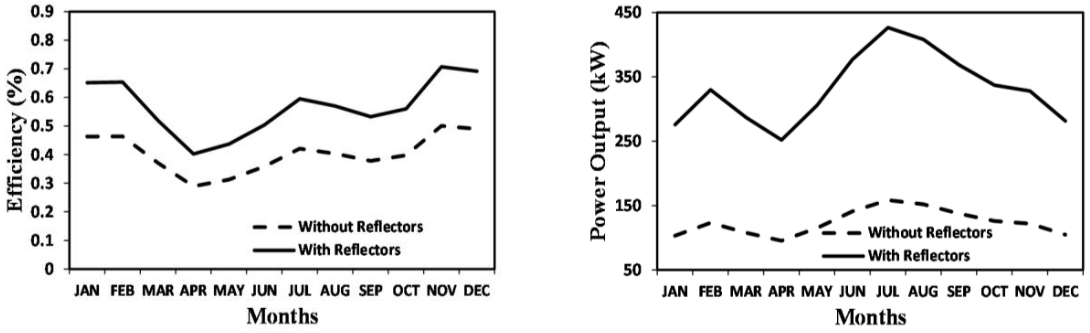


3 (a) **3 (b)**

Fig. 3: (a) Variation of mass flow rate. (b) Variation of velocity at the inlet of turbine.

Theoretical power output and efficiency of SCPP model for both the cases are determined and summarized in Fig. 4. Increase in power output due to reflectors is found to be 167% whereas efficiency was increased by 40%, which is much higher than the design suggested by Pasumarthi and sherif (Pasumarthi and Sherif 1997, 1998a, 1998b).

From Fig. 2(a). Fig. 4(a). Fig. 4(b). an important conclusion can be drawn though the energy output was found to be less for the months of January and December, but SCPP model is found to have a maximum efficiency during this period, it is because of the fact that the velocities obtained are less which increases the duration of contact between air and floor in which air absorbs more heat from floor, when compared with summer months; thereby making the system more efficient for the winter months but less energy output because of lower solar irradiation.



4 (a) 4 (b)

Fig. 4: (a) Variation of efficiency. (b) Variation of energy output of the SCPP model.

5. Conclusions

This paper presents the enhanced performance analysis of the SCPP model with the aid of reflectors by increasing the radiant energy incident on to the floor and presents its performance for Dhahran, Saudi Arabia.

- It can be concluded that, the energy output is nearly directly dependent on the mass flow rate, which in turn is dependent on the geometry of the model, wind speed, and density.
- The reflector aided SCPP has an average air mass flow rate of around 432 kg/s, when compared with traditional SCPP which has an air mass flow rate of 158 kg/s.
- The SCPP aided with reflector is found to increase floor temperature by 9.3%.
- The reflector aided SCPP can produce on average, around 331kW during daytime when compared with traditional SCPP of same geometry which produces 123kW.
- The energetic efficiency found to increase by 40% and energy output is increased by 167%.

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