THERMAL PERFORMANCE ANALYSIS OF HELICAL COIL SOLAR CAVITY RECEIVER BASED PARABOLIC TROUGH CONCENTRATOR

Arun Kumar and S.K.Shukla*

Centre for Energy and Resources Development, Department of Mechanical Engineering,Indian
Institute of Technology (Banaras Hindu University), Varanasi-221005, India

*Corresponding author; E-mail: shuskla@gmail.com

The present paper investigates the performance of helical coil solar cavity receiver based parabolic trough concentrator (PTC) for the conversion of energy received from the sun into useful heat and finally electricity. The experimental setup has been designed in such a way that it enhances heat transfer coefficient and reduces losses in the PTC. The PTC comprised of a blackened helical coil made up of two concentric borosilicate glass cylinder with vacuum in the annulus, which is kept at a focal line of PTC. The vacuum significantly reduces the losses which are evident from a relatively higher temperature of a 565K obtained at the surface of the helical coil.Heat loss from helical coil solar cavity receiver has also been investigated and it was found that with the increase in vacuum pressure at annulus by 50%, the losses from the receiver has been increased by 26.67%. The heat loss from receiver has been observed to be proportional to the vacuum pressure within the annulus space.

Keywords*: "Helically coiled tube", "double glazing surface", "heat collecting element", "vacuum tube outer cell".*

1. Introduction

The application of solar energy is one of the best ways to face global challenges as the climate change. In order to supply more and more thermal output, solar energy is often used in power plants[1]. Among all the concentrated solar power technology, parabolic trough concentrator is the most advanced technology for power generation[2]. A parabolic trough concentrator is a line focusing solar collector that is straight in one dimension and curved as a parabolic shape in the other two dimensions. It is lined with mirror film of high reflectivity[3–6]. Solar radiation, which enters the PTC parallel to the plane of symmetry, is concentrated along the focal line, where a tube receiver is installed to receive the concentrated solar radiation[7,8]. The receiver is the heart of concentrated solar power (CSP) system. And so, Many researchers pay attention towards the design of a variety of solar receivers so that the thermal performance of CSP system can be improved. Evangelos Bellos et al[9] use internal fins, attached longitudinally with the inner surface of receiver pipe of the parabolic trough collector. The examined parameters for the analysis of the internally finned type solar receiver are the thermal enhancement index, the thermal efficiency, the pressure losses and the Nusselt number. They determined the optimum value of length and thickness of fins for the optimum thermal performance of PTC system. E. Bellos et al[10].studies the influence of receiver geometry on the collection efficiency of absorber tube. They designed the absorber pipe in such a way that the inner surface of the tube becomes a converging-diverging type. The sinusoidal variation of diameter along the length of receiver tube increases the inner heat transfer area for the heat transfer fluid together with it changes the flow regime from laminar to turbulent flow. They found that the increase in efficiency by 4.55%.The absorber with pin fin arrays inserting, presented by Gong Xiangtao et al[11]is more efficient than the simple horizontal tube receiver of a parabolic trough concentrator. Their model improves the overall heat transfer coefficient by 12%. The convective heat transfer coefficient can also be increased by inserting the twisted tape insert at the inner surface of the receiver tube. The presence of twisted tap is responsible for the rotation of flow in the axial direction thereby modifying the Reynolds and the Nusselt numbers[12].A Mwesigye et al.[13] investigates a thermal and thermodynamic performance of a receiver tube with perforated plate inserts for a parabolic trough solar collector and found the maximum thermal efficiency improvement as compared to smooth receiver in turbulent flow regime is 8%.

The solar receiver tube is generally surrounded by a glass tube to block infrared radiations and to reduce convective losses. Typically, the solar thermal power plants based on parabolic trough concentrator use evacuated space between the absorber tube and the glass tube to reduce heat losses and to increase thermal efficiency. Vacuum creation between receiver tube and the environment is fundamental to reduce heat loss in solar thermal application[14]. The vacuum and its lifespan will greatly affect the heat loss in a receiver[15]. Vacuum tube should be designed in such a way that there should not be any kind of vacuum loss i.e. working on vacuum leakage is also important. Li et al. [16] Analyses the different type reasons for vacuum loss in the annulus of the solar receiver. They concluded that the accumulation and infiltration of hydrogen are the main reasons for heat losses. Therefore, removal of hydrogen from the annulus space is essential. Although it is impossible to remove 100% hydrogen from the annulus space, maximum amount can be reduced by the process of degassing and usage of getters in the receiver. Liu J et al.[17]developed a receiver with borosilicate glass to metal seal. They claimed that it reduces the vacuum loss and hence the reduction of loss from the receiver thereby increasing the efficiency of the PTC system. Zhang et al.[18]experimentally investigated the effects of wind, vacuum glass tube, radiation, and structural characteristics of the heat losses. They concluded that the thermal efficiencies of the receiver were found to be 0.791 and 0.472 in calm and windy days, respectively, at a test temperature of about 100^{o}C.

After going through the various literature, it would be no exaggeration to say that the huge research has been done on the design and performance of the solar receiver. Most of the solar receivers of a parabolic trough concentrator are a horizontal tube or the tube with different inner surface geometry like internal fins, converging-diverging sinusoidal geometry, fin pin arrays, perforated plates, twisted tape inserts. But nobody has used the receiver of helical coil geometry for the improvement of performance of parabolic trough collector. This paper presents the design and performance of a novel receiver concept presented using thermal oil as heat transfer fluid for parabolic trough concentrators. The objective of the present study was to propose a double glazing helical coil solar cavity receiver with the vacuum tube outer cell to minimize losses and thereby enhancing the thermal efficiency of a parabolic trough concentrator.

2. Experimental procedure

Fig. 1 shows the photograph of experimental setup installed at the rooftop of CERD, Mechanical Engineering Department, IIT (BHU), Varanasi. The heart of the experimental setup is a line concentrating helical coil solar cavity receiver. Double glazing helical coil solar cavity receiver is kept at the focus of PTC with a focal length of 0.606m in order to ensure that the receiver is completely inside the cylindrical intense image formed by reflected sunlight from the aperture of parabolic trough concentrator. The experimental setup consists of a 0.5 HP centrifugal pump ensuring the thermal oil circulation through the helical coil solar cavity receiver. The circulated oil in the receiver is supplied from oil tank of 10-liter capacity. The flow rate of oil entering the receiver is measured by a flowmeter. The thermal oil gets heated while flowing through the well-focused receiver and exchange this heat to water in hot water tank of capacity 46 liters. The hot water tank is a shell and coil type heat exchanger where the oil is circulated through the coil dipped in water in the water tank. The inlet and outlet temperatures of oil are measured by thermocouple sensors which transmit the signals to a data logging facility connected to the present setup. A sun tracker continuously tracks the sun and as a result, the cycle can run efficiently. The tracker tracks the sun on an hourly basis by rotating the PTC at a 15° angle per hour. It should be noted that the system operates in a closed cycle and the effect of all the environmental parameters such as wind speed, wind direction, relative humidity, air temperature, dust/dirt and solar radiation are taken into account.Helical coil receiver has been enclosed with two concentric borosilicate glass covers with vacuum at the outer annulus as shown in the Fig.1. Parallel rays of solar radiation incident on the aperture and concentrated at the focus where the receiver is placed. The main function of the receiver is to convert solar energy into thermal energy in terms of heated oil. In the present experimental setup, the performance of evacuated tube helical coil solar cavity receiver has been analyzed and compared with the empty tube receiver.

In the present linear concentrating parabolic trough collector, the concentration ratio is 20.31.Further; the data on experimental setup are collected on different days daily from January to June 2017. However, some of the collected data around the days have been used for performance analysis.

Table 1. Specification of experimental set up

Experimental set up parts	Dimensions
Length of helical coil	5.172 m
Perimeter of copper tube	0.02188 m
Receiver Area	0.113716 m
Parametric length of receiver	1.8432 m
Width of collector	1.220 m
Aperture Area	2.2487 m
Concentration Ratio	19.77 m
Diameter of Helical circle(D)	25 mm
Diameter of Cu Tube(d)	5 mm
Thickness of Cu Tube(t)	1 mm
Pitch of Helical coil(P)	24.38 mm
Number of turns(N)	50 mm

3. Numerical methodology

Fig. 2 shows actual design dimensions of double glazing helical coil solar cavity receiver. The geometrical parameters and material specifications are given in Tab.1.

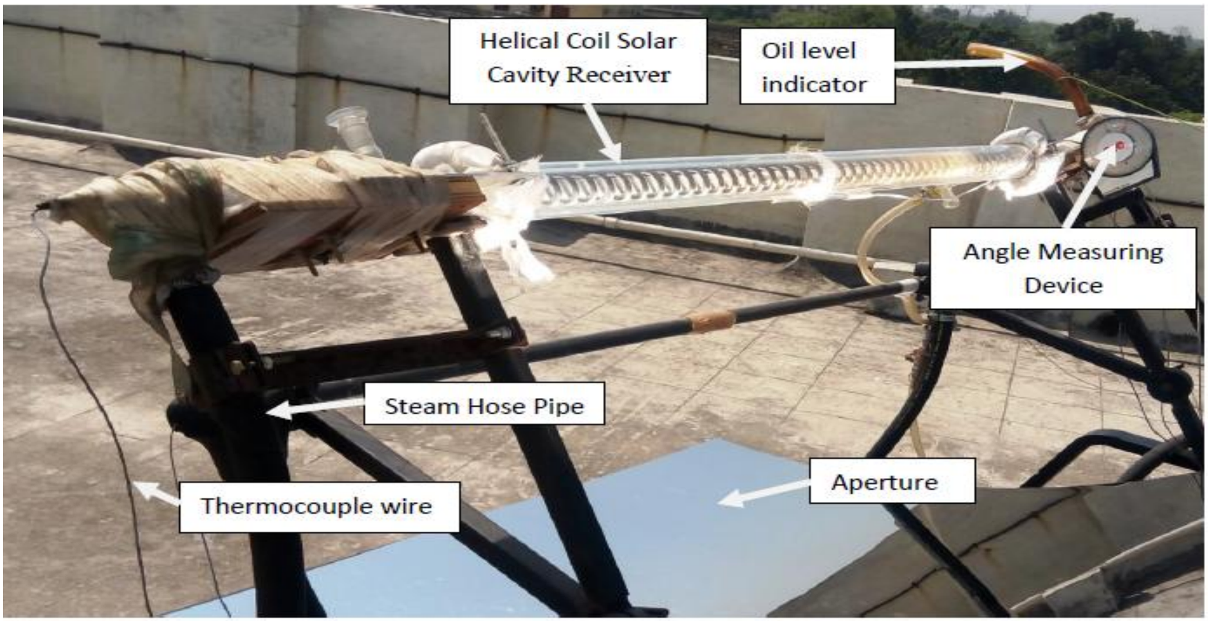

Figure 1. Line concentrating helical coil solar cavity receiver at CERD, IIT (BHU), Varanasi

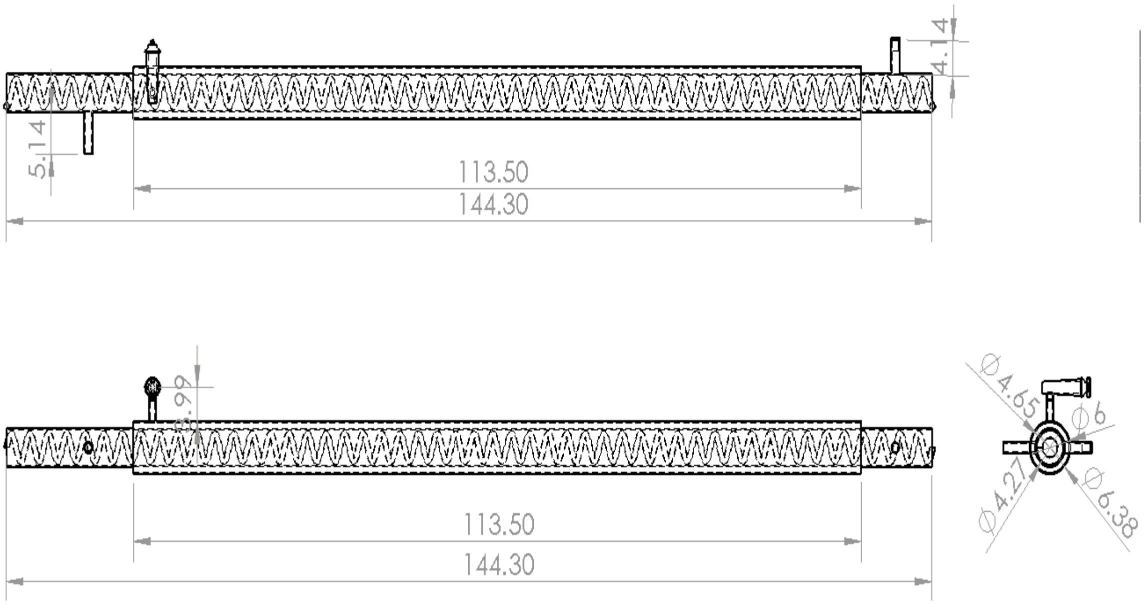

Figure 2. Shows the designed dimension of the experimental set up at CERD,IIT (BHU),Varanasi

3.1. Total length of the helical coil (L)

Perimeter of the copper tube (p) = $\pi \times d$ (1)

Total length of the helical coil (L) = $n \times l$ (2)

Helical coil in one turn (l) = $\sqrt{P^2 + \pi^2 D_1^2}$ (3)

$$= \sqrt{\left(P^2 + \pi^2 (D + d + 2t)^2\right)} \tag{4}$$

$$L = \left(P^2 + \pi^2 D^2 \left(1 + \delta + \frac{2t}{D} \right)^2 \right)^{\frac{1}{2}} \times l \tag{5}$$

3.2. Equation of parabolic trough collector

$$y = ax^2 \ or \ x^2 = \left(\frac{1}{a}\right) \times y \ or \ \left(\frac{1}{a}\right) = 4f = 4 \times 0.6065 = 2.426 \tag{6}$$

$$y = \left(\frac{50}{121.3}\right) x^2 \tag{7}$$

$$\frac{dy}{dx} = \frac{100}{121.3} x \tag{8}$$

3.3. Length of the PTC curve (S)

$$S = 2 \times \int_0^{0.855} \left(1 + \left(\frac{100}{121.3}\right)^2 x^2\right)^{\frac{1}{2}} dx \tag{9}$$

3.4. Concentration ratio (C.R) of PTC system

$$C.R = \frac{\mathrm{S \times b}}{\pi d \left(P^2 + \pi^2 D^2 \left(1 + \delta + \frac{2t}{D}\right)^2\right)^{\frac{1}{2}} \times l} \tag{10}$$

3.5. Heat loss equation model

The following assumptions are made to derive the equation for PTC.

- The PTC system is operated in steady state mode.
- The heat transfer fluid, therminol VP-1 is incompressible.
- Mass flow rate of thermal oil is kept constant at any temperature.
- Viscosity of heat transfer fluid changes with time.

Energy balance equation for helical coil solar cavity receiver has been given in Eq. 5 main challenge here is to find out the overall loss coefficient.

$$Q_u = A_h \times CR \times I \tau^N \alpha - U_t A_g \left(T_{pm} - T_a\right) \tag{11}$$

3.6. Conversion efficiency helical coil receiver

The conversion efficiency is the ratio of thermal output by receiver to the sun energy input to the aperture of concentrating collector and can be calculated as:

$$\eta_c = \frac{Q_u}{I_b \times A_{Sa}} \tag{12}$$

$$Q_u = \dot{\mathrm{m}} \times \mathrm{c_p} \times \left(\mathrm{T_o} - T_i\right) \tag{13}$$

Where Q_u is the useful energy gain, I_b and A_{sa} are the direct solar radiation intensity and aperture area respectively. $T_o$and T_i is the temperatures at the inlet and at the exit of the receiver.

Table.2 Experimental observations of April 24, 2017, for parabolic trough concentrator.

Time (Hrs.)	Hot Water Temp (^oC)	Absorber inlet temp (^oC)	Absorber outlet temp (^oC)	Absorber tube temp (^oC)	Tank inlet temp (^oC)	Tilt angle	Helical coil temp. (^oC)	Supporting rod temp (^oC)	Mass flow rate (in LPM)	Surface Azimuth
09:30	34	45	62.4	88	51.4	40	64	37.5	5.57	80
10:00	35	45.9	54.6	75	57.1	35	58	36.4	5.88	80
10:30	38.4	49.9	55.7	74	68.6	29	55	38.9	5.88	70
11:00	42	52.5	59.4	88	64.3	23	58	41.7	3.97	60
11:30	45.5	56.3	60	73	65.3	16	56.5	42.5	5.13	40
12:00	48.5	57.9	60.5	63	65.3	15	57.5	42.8	5.57	20
12:30	51.2	60.7	64.7	78	66.4	16	62	44	5.88	-25
01:00	53.5	60.2	63.7	67	66.9	24	61.5	45.7	5.88	-45
01:30	55.2	61.5	66.5	73	69.1	29	65.5	46.2	5.88	-72
02:00	57.2	64.5	66.4	69	69.5	35	62.5	47.2	5.88	-80
02:30	59	66.7	68.4	65	71.8	41	65	48	5.88	-85
03:00	60.5	64.6	67.2	57	70.4	48	62	47.7	5.88	-90
03:30	61.4	62.6	63.5	45	67	51	59.5	44.8	5.88	-90

Table. 3 Environmental data during the month of April on dated 24-04-2017 at CERD, IIT(BHU), Varanasi

Time	Direct solar radiation (W/m^2)	Diffuse solar radiation (W/m^2)	Air Temp.(0˚C)	Air speed m/s	Wind Direction (W-N)	RH (%)
08:00	514	227	32.7	1.5	242	41
09:00	594	236	33.1	0.7	73	41
10:00	765	260	34.2	0.5	170	37
11:00	811	279	36.4	0.7	174	39
12:00	790	279	38.1	1.8	37	35
13:00	731	267	39.6	1.2	54	26
14:00	610	260	40.6	1.2	179	27
15:00	431	223	41.9	0.4	75	22
16:00	127	114	40.7	1.7	102	28
17:00	94	94	40.5	1.9	83	28
18:00	19	14	39.6	0.3	77	31

4. Uncertainty analysis

A complete uncertainty analysis is performed on the experimental data on April 24, 2017, as shown in the appendix as mentioned at the end of the paper. The analysis takes into account the uncertainties in measured parameters like mass flow rate of heat transfer fluid, ambient temperature, concentration ratio, parametric length of the collector, the aperture area of PTC, solar radiation intensity and wind speed as shown in Tab. 2. The uncertainty associated with aperture area is 2.2296732 ± 0.01903. Hence, using the Eq. 7 and Eq. 8 the uncertainty associated with concentration ratio is found to be 19.77± 0.54.

$$R = f(X_1, X_2, X_3, ..., X_N), \quad R^* = any \ \ function$$

$$\sigma_R = f(\sigma_{X_1}, \sigma_{X_2}, \sigma_{X_3} ....\sigma_{X_N}), \sigma_R = Uncerta\text{int } y \text{ in R}$$

$$\sigma_R = \pm\sqrt{\left(\sum_{i=1}^{N}\left(\frac{\partial R}{\partial X_i}\partial X_i\right)^2\right)}, \tag{14}$$

$$U_R = \pm\sqrt{\left(\frac{1}{R^2}\sum_{i=1}^{N}\left(\frac{\partial R}{\partial X_i}\partial X_i\right)^2\right)} \tag{15}$$

U_R = Relative uncertainty

Table 4. Uncertainties in the experiments

Measured parameters	Uncertainty
Mass flow rate	0.0960
Ambient temperature	0.0590
Concentration ratio	0.0270
Parametric length of collector	0.0076
Aperture area of PTC	0.0085
Solar radiation intensity	0.1700
Wind speed	0.5700

5. Results and discussion

The performance analysis has been done using experimental data obtained on the experimental setup on typical days March, April 2017. In the present experimental setup, losses have been minimized using helical coil solar cavity receiver with the double glazing vacuum tube outer cell. The present research provides a comprehensive design of helical coil solar cavity receiver and its performance analysis under the Varanasi climatic zone. A blackened helical coil copper absorber tube was covered with two concentric borosilicate glass having vacuum at annulus, kept at the focal line of a parabolic trough concentrator. A parabolic trough concentrator with an aperture area of 2.229673 m² and receiver area of 0.113716 m² was kept under solar radiation intensity in such a way that surface azimuth and tilt angle of the system became equal to solar azimuth and zenith angle respectively. The validation of model used in this analysis has been done using EES software. Input parameters have been obtained on experimental set updated from 03.04.2017 to 14.05.2017 with the variation of vacuum pressure from 1 torr to 760 torr. Following are the results which have been obtained on experimental set up and explained below.

5.1. Climatic parameters

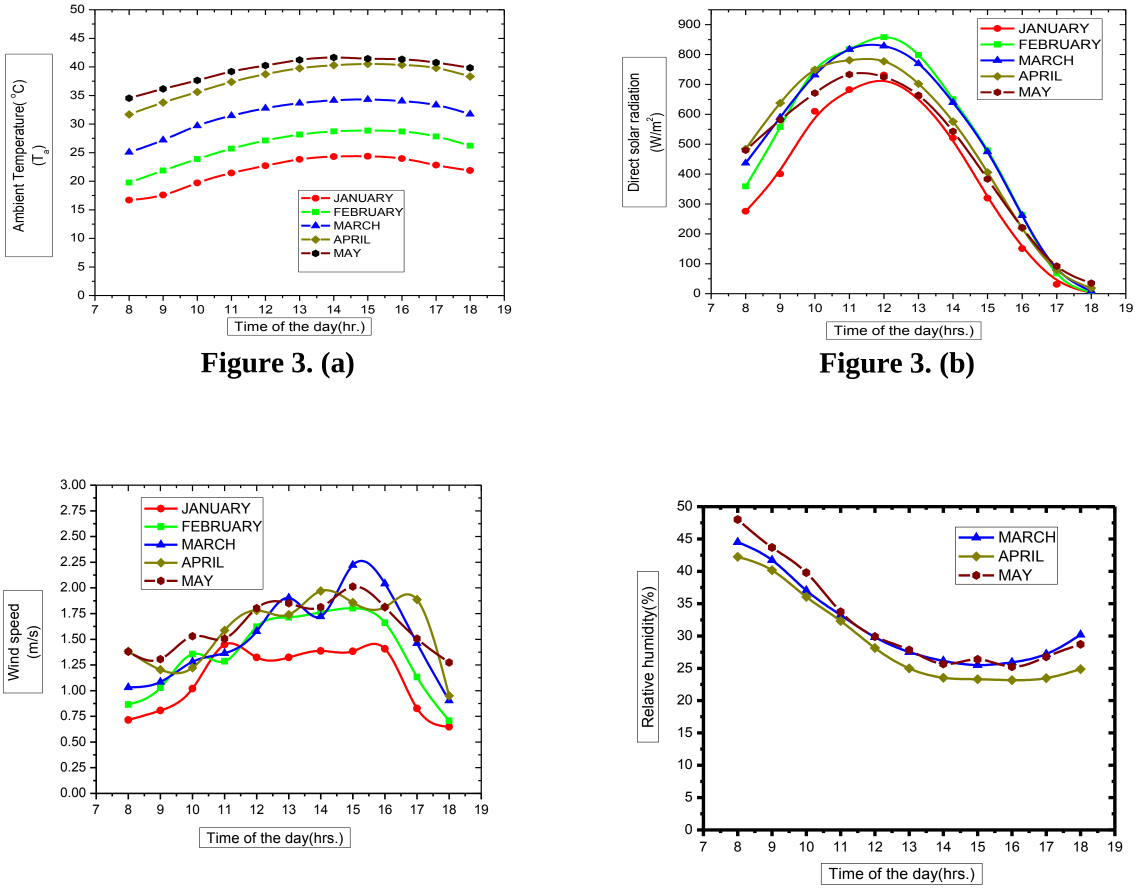

Figure 3. (a)

Figure 3. (b)

Figure 3. (c)

Figure 3. (d)

Fig. 3 (a) to 3(d) show the variation of ambient temperature, direct solar radiation, wind speed and relative humidity with time of the day.

From Fig. 3(a) to 3(d) show the variations of environmental parameters like ambient temperature, direct solar radiation, wind speed and relative humidity with respect to time of the day on dated January to May, 2017.. High value of air temperature reduces convection loss from helical coil solar cavity receiver. Parabolic trough technology performs well at high value of direct radiation and low value of air speed. Solar radiation intensity, Wind speed and its direction were measured by weather monitoring station installed at roof top near experimental set up at CERD, IIT (BHU). Fig. 3(c) shows clearly that the wind speed is fluctuating in nature with respect to time of the day thereby too much sensitive in the performance analysis of PTC system. Direction of air speed plays vital role in losses because parabolic trough concentrator is a line concentrating unit. When air flows along the length of helical coil, losses will be higher in comparison to the flow of air in any other directions. Relative humidity affects the solar radiation intensity. Increase in the value of relative humidity will increase the percentage of water droplets thereby increase in scattering effect and hence reduce the intensity of solar radiation. Optical path length is also affected by relative humidity. Direct solar radiation intensity reduces as the optical path length or air mass increases during the day hour. Environmental parameters are vital in solar thermal applications and hence environmental data analysis is important for the best study of solar parabolic trough concentrated technology.

5.2. Performance parameters

5.2.1 Conversion efficiency

In this section, an experimental analysis to determine the performance of the parabolic trough concentrator has been carried out under the climatic conditions of Varanasi (Latitude 25.31 and Longitude: 82.97), Uttar Pradesh, India. Since, the meteorological cycle on average repeats itself every year, the results presented here would be invariant of change in year. Fig. 4 shows the comparision between the helical coil receiver and the horizontal tube receiver of the parabolic trough concentrator in terms of conversion efficiency.

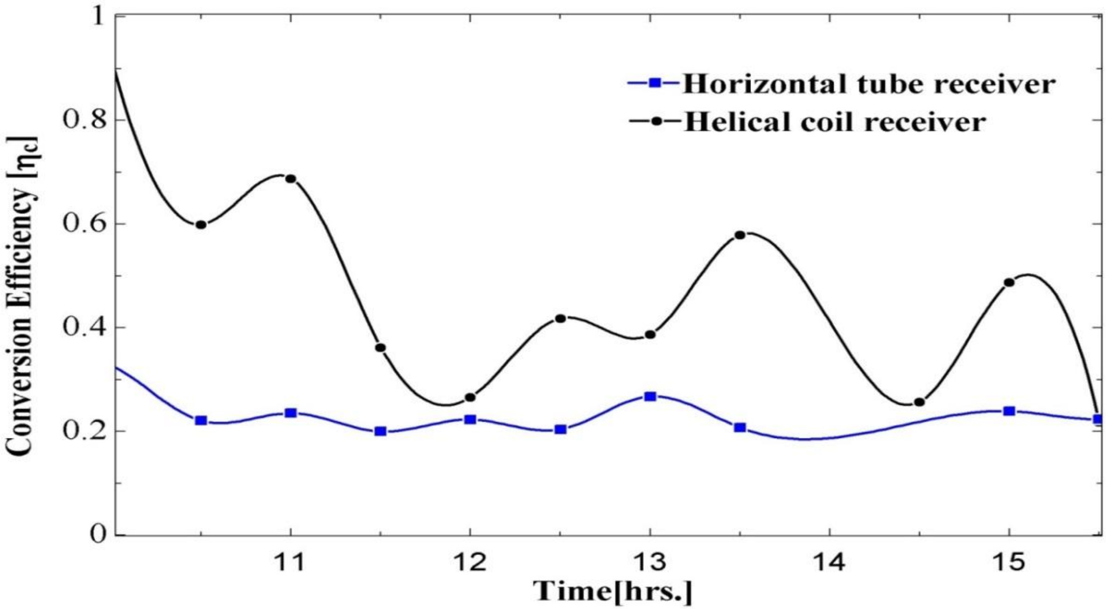

Figure 4. Comparision of double glazing helical coil receiver with the horizontal tube receiver under the enviromental contions: solar radiation intensity range 600 - 900 W/m^2 and the wind speed range 0.3- 2.0 m/s.

Fig. 4 represents how the conversion efficiency of double glazing helical coil receiver and empty horizontal tube receiver (non evacuated) varies with respect to the time of the day. Above figure for conversion efficiency has been plotted considering all environmental conditions of Varanasi climatic zone with solar radiation intensity range 600 - 900 W/m^2 and the wind speed range 0.3 - 2.0 m/s. The x-axis represents the time of the day in the plot because all the parameters that affect the conversion efficiency depend upon the time. Solar radiation intensity, wind speed, wind direction, air temperature and relative humidity all these parameters vary from morning to evening. It was found clearly from the plot that the maximum conversion efficiency for bare horizontal tube receiver and evacuated helical coil receiver are 31% and 85% respectively. However, some of the researchers like Milton Matos Rolim et al. (2009)[19] and of Dudley et al. (1994)[20] examines the variation of conversion efficiency for evacuated horizontal tube receiver with respect to the temperature difference which exists between mean fluid temperature and the ambient temperature. They found the maximum conversion efficiency of 73%. Ricardo Vasquez Padilla et al.(2011)[21] also study the variation of conversion efficiency with the average temperature of the receiver above ambient in the case of evacuated horizontal tube receiver and found the maximum conversion efficiency of 73%. In all those cases, the receivers are single glazing evacuated horizontal tube and conversion efficiency being a continuously decreasing function. In the case of double glazing evacuated helical coil solar cavity receiver, this function is not continuous but shows the continuous formation of maxima and minima in the plot. This is due to the fluctuation of solar radiation intensity and wind speed during sunshine hour. On the whole, it can realize that the conversion efficiency depends on mainly the two thinks, first the environmental conditions and second the design of receiver system. It will be some what difficult to control over the environmental changes but the efficient design of solar receiver is totally in our hand.

5.2.2 Effect of vacuum pressure and wind speed

It is novel to create a vacuum in the annulus to minimize losses in PTC system. Fig. 5 shows clearly the variation of heat losses with annulus vacuum pressure under the Varanasi climatic conditions during the months of March to June, 2017. Result shows that the vacuum level is a parameter that strongly affects heat losses from helical coil solar cavity receiver. Pressure in the annulus is varied from 10 torr to 50 torr during the course of the experiment. The pressure greater than 50 torr add to tremendous losses where as the vacuum pressures below 10 torr contribute significantly to the performance of system owing to reduce more losses. Effect of pressure at annulus on heat loss has been investigated by R. Vinuesa et al.(2016)[22]. They kept air and hydrogen separately in the vacuum chamber below 10 torr and analyse the loss due to convection from evacuated metallic tube receiver. R. Forristall (2003) prepared a technical report under National Renewable Energy Laboratory, U.S. Department of Energy Laboratory, presents the variation of heat loss per unit length of receiver with respect to the annulus pressure in torr. Annulus pressure was varied from 0.0001 torr to 1000 torr and losses has been observed for single glazing evacuated metallic tube receiver. The plot in this report shows clearly that the pressure in the vacuum chamber below 0.1 torr adds maximum to the performance of parabolic trough receiver. The vacuum chamber pressure greater than 100 torr increase losses rapidly thereby reduce thermal performance. In the present work, the pressure in the vacuum chamber has been varied between 10 torr to 50 torr to analyze the performance of double glazing helical coil solar cavity receiver with vacuum chamber at the outer annulus. The trough and crest formation in Fig. 5 is due to the flow of wind along or across the length of helical coil solar cavity receiver and the impact of relative humidity. The appearance of maxima and minima on the above plot is very interesting and it includes the effect of all environmental parameters described earlier. Solar radiation intensity on earth's surface is affected by relative humidity but it is beam radiation, not the global radiation that is affected by relative humidity.

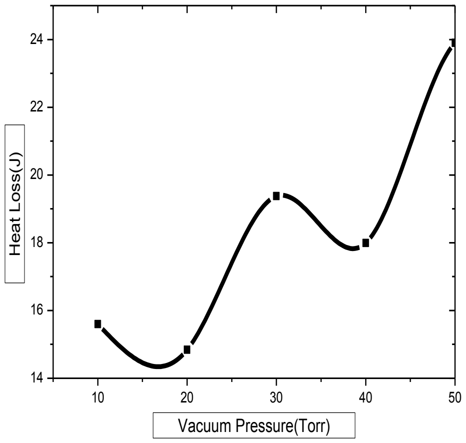

Figure 5. Shows the variation of heat loss with respect to vacuum pressure

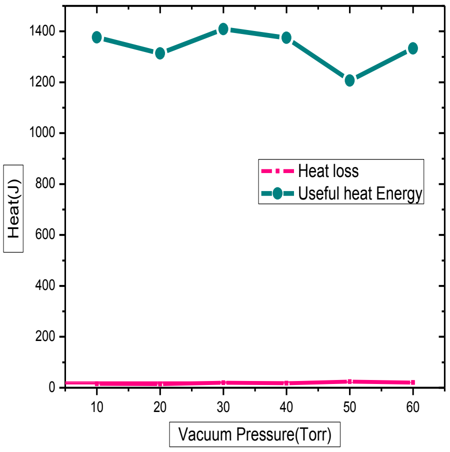

Figure 6. Shows the variation of useful energy and heat loss with vacuum pressure.

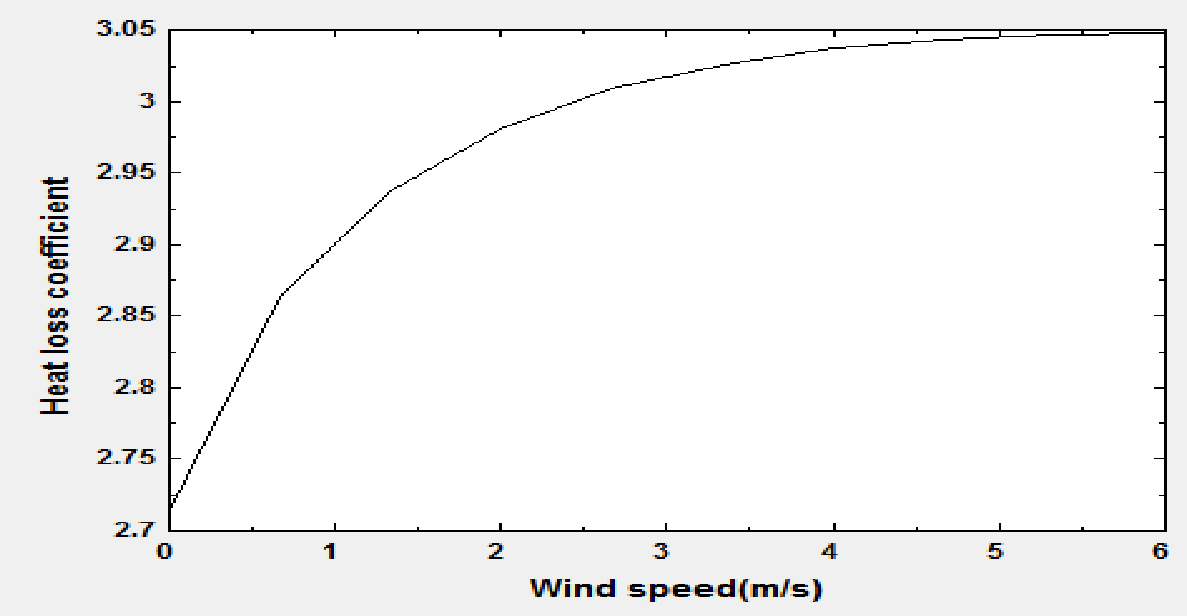

Figure 7. Shows the variation of heat loss coefficient with respect to wind speed.

The values of relative humidity, solar radiation intensity and ambient temperature for the month of April 2017 at 01:00 are 26%, 731 W/m^{2,} and 39.6 ^{o}C respectively as shown in environmental data Tab. 3. It was found that 3.84% increase in relative humidity is responsible the decrease in the intensity of solar radiation by 16%. Antonio J. Gutiérrez-Trashorras et al.(2018)[23] reported in their paper the variation of monthly average solar radiation in the clean and turbid atmosphere and prove the effect of relative humidity on solar radiation. Jiann Lin Chen et al.(2017)[24] also presented the variation of solar irradiance with relative humidity. They found that 0.91% increase in relative humidity is responsible for the decrease in the intensity of solar radiation by 12.58%.Another environmental parameter that affects the formation of maxima and minima in the above plot under discussion is wind speed. It has been shown clearly in the Fig. 7 that how the heat loss coefficient varies with respect to wind speed when the solar receiver is exposed to the atmosphere. McAdams (1954) suggests the effect of wind speed on loss coefficient over flat plate collector. He found that the trend is linear with a constant slope 3.8 but the trend becomes nonlinear with decreasing slope in the case of the flow of wind over helical coil solar cavity receiver. Fig. 6 shows the difference between useful energy gain and heat losses. Useful energy curve appears at the top of the plot while the heat loss curve appears at the bottom of the plot. This significant difference between the useful energy gain and heat loss shows the beauty of helical coil solar cavity receiver.

6. Conclusions

The present study examines the experimental analysis of double glazing helical coil receiver of the parabolic trough concentrator. The receiver used in the present analysis is compared with the empty tube (non evacuated) receiver for the same receiver length. It was found that the maximum conversion efficiency for empty tube receiver and evacuated helical coil receiver are 31% and 85% respectively for the thermal oil flow rate of 5.88 L/minute. This drastic change in the value of maximum conversion efficiency is due to the reasons: first, the horizontal empty tube is converted into helical coil tube which is accountable for the enhancement of the convective heat transfer coefficient owing to the secondary flow and second, the double glazing evacuated tube over helical coil responsible for the reduction of losses due to conduction and convection. Heat loss from helical coil solar cavity receiver has also been investigated by varying vacuum pressure at the annulus. It was observed that if the vacuum pressure at annulus increases from 20 torr to 30 torr, the losses from the receiver increases from 15J to 19J i.e. 26.67% loss occur if vacuum pressure increases by15% in the vacuum chamber. Hence, creating vacuum at annulus is one of the best way to minimize losses from the solar receiver. The effect of wind has also been analyzed on solar receiver. The overall heat loss coefficient was changed from 2.7 W/m^2–K to 3.05 W/m^2–K as the wind speed changes from 0 m/s to 6 m/s.

Acknowledgment

The authors gratefully acknowledge the MHRD, New Delhi for financial support for conducting this study.

Nomenclature

A_g	Surface area of outer glass(m^2)	T_a	Ambient temperature(K)
A_h	Helical coil surface area(m^2)	T_i	Absorber inlet temperature(K)
d	Helical coil tube diameter(m)	T_o	Absorber outlet temperature(K)
D	Helix diameter(m)	T_{pm}	Mean coil temperature(K)
D_1	D+2t (m)	*Greek symbols*	
h_w	Wind heat transfer coefficient(W/m^2-K)	α	Absorptivity of copper receiver
I	Beam radiation (W/m^2)	β	Collector tilt angle(degree)
l	Pitch of the coil(m)	ε_g	Emitance of glass
L	Total length of helical coil(m)	ε_p	Emitance of coil
n	Number of turns	σ	Boltzman constant ($5.67X10^{-8}$)
N	Number of glass covers	τ	Transmitivity of borosilicate glass
Q_u	Useful energy gain (J)	*Abbreviation*	
t	Thickness of copper tube (m)	CR	Concentration ratio

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