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

### by

## Arun KUMAR and Shailendra Kumar SHUKLA\*

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

> Original scientific paper https://doi.org/10.2298/TSCI170830104K

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 set-up 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 565 K 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.

Key words: helically coiled tube, double glazing surface, heat collecting element, vacuum tube outer cell

### 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 (CSP) technology, PTC is the most advanced technology for power generation [2]. A PTC 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 CSP system. 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. 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. Bellos et al. [10] studies the influence of receiver geometry on the collection efficiency of absorber tube. They designed the absorber

<sup>\*</sup> Corresponding author, e-mail: shuskla@gmail.com

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 Xiangtao *et al.* [11] is more efficient than the simple horizontal tube receiver of a PTC. 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]. 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 PTC 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. Wu 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 °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 PTC 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 PTC. 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.

# **Experimental procedure**

Figure 1 shows the photograph of experimental set-up installed at the rooftop of CERD, Mechanical Engineering Department, IIT (BHU), Varanasi. The heart of the experimental set-up 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 0.606 m

3540

Kumar, A., *et al.*: Thermal Performance Analysis of Helical Coil Solar Cavity Receiver ... THERMAL SCIENCE: Year 2019, Vol. 23, No. 6A, pp. 3539-3550

3541

in order to ensure that the receiver is completely inside the cylindrical intense image formed by reflected sunlight from the aperture of PTC. The experimental set-up consists of a 0.5 HP (373 W) 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 L 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



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

this heat to water in hot water tank of capacity 46 L. 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 set-up. 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 set-up, 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 set-up are collected on different days daily from January to June 2017. However, some of the col-

lected data around the days have been used for performance analysis.

## Numerical methodology

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

# Total length of the helical coil

- Perimeter of the Cu tube:

$$p = \pi d \tag{1}$$

abl	e 1	Specif	ication	of	exper	iment	al	set	up	

insie it 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	25 mm				
helical circle, D					
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				



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

- Total length of the helical coil:

$$L = nl \tag{2}$$

- Helical coil in one turn:

$$l = \sqrt{P^2 + \pi^2 D_1^2} =$$
(3)

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

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

# Equation of parabolic trough collector

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

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

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

# Length of the PTC curve

$$S = 2 \cdot \int_{0}^{0.855} \left[ 1 + \left(\frac{100}{121.3}\right)^2 x^2 \right]^{\frac{1}{2}} dx$$
(9)

Concentration ratio of PTC system

$$CR = \frac{Sb}{\pi d \left[ P^2 + \pi^2 D^2 \left( 1 + \delta + \frac{2t}{D} \right)^2 \right]^{\frac{1}{2}} l}$$
(10)

Kumar, A., *et al.*: Thermal Performance Analysis of Helical Coil Solar Cavity Receiver ... THERMAL SCIENCE: Year 2019, Vol. 23, No. 6A, pp. 3539-3550

### 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.

$$Q_u = A_h \cdot CR \cdot I\tau^N \alpha - U_t A_g (T_{pm} - T_a)$$
<sup>(11)</sup>

### 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:

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

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

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

# **Uncertainty analysis**

A complete uncertainty analysis is performed on the experimental data on April 24, 2017, tab. 2. The analysis takes into account the uncertainties in measured parameters like mass-flow rate of heat transfer fluid, ambient temperature, CR, parametric length of the collector, the aperture area of PTC, solar radiation intensity and wind speed as shown in tab. 3. The uncertainty associated with aperture area is  $2.2296732 \pm 0.01903$ . Hence, using the eqs. (7) and (8) the uncertainty associated with concentration ratio is found to be  $19.77\pm 0.54$ , tab. 4.

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

				<b>^</b>		-				
Time [h]	Hot water temp. [°C]	Absorber inlet temp. [°C]	Absorber outlet temp. [°C]	Absorber tube temp. [°C]	Tank inlet temp. [°C]	Tilt angle	Helical coil temp. [°C]	Supporting rod temp [°C]	Mass flow rate [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

$$R = f(X_1, X_2, X_3, \dots, X_N), \quad R^* = \text{any function}$$
  
$$\sigma_R = f(\sigma_{X_1}, \sigma_{X_2}, \sigma_{X_3}, \dots, \sigma_{X_N}), \quad \sigma_R = Uncerta \text{ int } y \text{ in } R$$

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

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

where  $U_{\rm R}$  = relative uncertainty.

Table 3. Environmental data during the month of April on dated24-04-2017 at CERD, IIT (BHU), Varanasi

Time	Direct solar radiation [Wm <sup>-2</sup> ]	Diffuse solar radiation [Wm <sup>-2</sup> ]	Air temperature [°C]	Air speed [ms <sup>-1</sup> ]	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

Table 4.	Uncertainties	in	the	experiments
	C		****	

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		

#### **Results and discussion**

The performance analysis has been done using experimental data obtained on the experimental set-up on typical days March-April 2017. In the present experimental set-up, 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 PTC. A PTC with an aperture area of 2.229673 m<sup>2</sup> and receiver area of 0.113716 m<sup>2</sup> 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 April 3, 2017 to May 14, 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.

\* 760 torr =  $101325 \text{ Pa} = 1.01325 \cdot 10^5 \text{ Pa}$ 

Kumar, A., *et al.*: Thermal Performance Analysis of Helical Coil Solar Cavity Receiver ... THERMAL SCIENCE: Year 2019, Vol. 23, No. 6A, pp. 3539-3550

### **Climatic parameters**

From figs. 3(a)-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). Figure 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 PTC 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.



Figure 3. (a) Show the variation of ambient temperature, (b) direct solar radiation, (c) wind speed, and (d) relative humidity with time of the day

### **Performance parameters**

# Conversion efficiency

In this section, an experimental analysis to determine the performance of the PTC 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. Figure 4 shows the com-



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

parision between the helical coil receiver and the horizontal tube receiver of the PTC in terms of conversion efficiency.

Figure 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. The figure for conversion efficiency has been plotted considering all environmental conditions of Varanasi climatic zone with solar radiation intensity range 600-900 W/m<sup>2</sup> 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 param-

eters 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 Rolim et al. [19] and Dudley et al. [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%. Padilla et al. [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.

## Effect of vacuum pressure and wind speed

It is novel to create a vacuum in the annulus to minimize losses in PTC system. Figure 5 shows clearly the variation of heat losses with annulus vacuum pressure under the Varanasi climatic conditions during the months of March-June, 2017. Result shows that the vacuum level is a parameter that strongly affects heat losses from helical coil solar cavity receiver.

#### 3546

Kumar, A., et al.: Thermal Performance Analysis of Helical Coil Solar Cavity Receiver ... THERMAL SCIENCE: Year 2019, Vol. 23, No. 6A, pp. 3539-3550

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 Vinuesa et al. [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. Forristall [23] 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



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

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.

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<sup>2</sup>, and 39.6 °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%. Gutierrez-Trashorras et al. [24] 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. Chen et al. [25] 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 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. Willians [26] 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 non-linear with decreasing slope in the case of the flow of wind over helical coil solar cavity receiver. Figure 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.



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

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

### Conclusion

The present study examines the experimental analysis of double-glazing helical coil receiver of the PTC. 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 lpm. 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 15 J to 19 J i. e. 26.67% loss occur if vacuum pressure increases by 15% 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<sup>2</sup>K to  $3.05 \text{ W/m}^2\text{K}$  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

- surface area of outer glass, [m<sup>2</sup>]
- helical coil surface area, [m<sup>2</sup>]  $A_{\rm h}$
- D helix diameter, [m]
- $D_1$ - (= D + 2t), [m]
- helical coil tube diameter, [m] d
- wind heat transfer coefficient, [Wm<sup>-2</sup>K<sup>-1</sup>]  $h_{w}$
- beam radiation, [Wm<sup>-2</sup>]
- \_ L total length of helical coil, [m]

- pitch of the coil, [m]
- number of glass covers N
- number of turns п
- Р \_ pitch of Helical coil
- $Q_{\rm u}$  $T_a$  $T_i$  $T_o$ useful energy gain, [J]
- \_ ambient temperature, [K]
- absorber inlet temperature, [K]
- absorber outlet temperature, [K]

Kumar, A., *et al.*: Thermal Performance Analysis of Helical Coil Solar Cavity Receiver ... THERMAL SCIENCE: Year 2019, Vol. 23, No. 6A, pp. 3539-3550

$T_{pm}$ - mean coil temperature, [K] t - thickness of copper tube, [m]	$\sigma$ – Boltzman constant, (= 5.67 · 10 <sup>-8</sup> ) $\tau$ – transmitivity of borosilicate glass
Greek symbols	Acronyms
$\alpha$ – absorptivity of copper receiver	CR – concentration ratio

#### References

- Bellos, E., Tzivanidis, C., A Detailed Exergetic Analysis of Parabolic Trough Collectors, *Energy Convers.* Manag., 149 (2017), Oct., pp. 275-292
- [2] Biencinto, M., et al., Performance Model and Annual Yield Comparison of Parabolic-Trough Solar Thermal Power Plants with Either Nitrogen or Synthetic Oil as Heat Transfer Fluid, Energy Convers. Manag. J., 87 (2014), Nov., pp. 238-249
- [3] Eck M, H. K., Heat Transfer Fluids for Future Parabolic Trough Solar Thermal Power Plants, in: Proceedings, ISES World Congr., (Ed. Gosmani, D. Y., Zhao, Y.,), Springer, Berlin, 2007, Vol. 1-5, pp. 1806-1812
- [4] Cheng ZD, X. R., et al., Three-Dimensional Numerical Study of Heat Transfer Characteristics in the Receiver Tube of Parabolic trough Solar Collector, Int. Commun. Heat Mass.. 37 (2010), 7, pp. 782-787
- [5] Qiu Y, T. W., et al., Thermal Performance Analysis of a Parabolic Trough Solar Collector Using Supercritical CO<sub>2</sub> as Heat Transfer Fluid under Non-Uniform Solar Flux, Appl. Therm. Eng., 115 (2017), Mar., pp. 1255-1265
- [6] Hachicha, O. A., et al., Heat Transfer Analysis and Numerical Simulation of a Parabolic trough Solar Collector, Appl. Energy., 111 (2013), Nov., pp. 581-592
- [7] Khanna S, S. S., Kedare, S. B., Deflection and Stresses in Absorber Tube of Solar Parabolic trough Due to Circumferential and Axial Flux Variations on Absorber Tube Supported at Multiple Points, *Sol. Energy*, 99 (2014), 1, pp. 134-151
- [8] Khanna, S, K. S., Singh, S, Explicit Expressions for Temperature Distribution and Deflection in Absorber Tube of Solar Parabolic trough Concentrator, *Sol. Energy*, 114 (2015), Apr., pp. 289-302
- [9] Bellos, E., et al., Thermal Enhancement of Parabolic trough Collector with Internally Fi Nned Absorbers, Sol. Energy, 157 (2017), Nov., pp. 514-531
- [10] Bellos, E., et al., Thermal Enhancement of Solar Parabolic trough Collectors by Using Nano Fl Uids and Converging-Diverging Absorber Tube, *Renew. Energy J.*, 94 (2016), Aug., pp. 213-222
- [11] Xiangtao, G., et al., Heat Transfer Enhancement Analysis of Tube Receiver for Parabolic trough Solar Collector with Pin Fin Arrays Inserting, Sol. Energy., 144 (2017), Mar., pp. 185-202
- [12] Jaramillo, M. R., O. A., *et al.*, Parabolic Trough Solar Collector for Low Enthalpy Processes: An Analysis of the Ef Fi Ciency Enhancement by Using Twisted Tape Inserts, *Renew. Energy J.*, 93 (2016), Aug., pp. 125-141
- [13] Mwesigye, A., et al., Heat Transfer and Thermodynamic Performance of a Parabolic Trough Receiver with Centrally Placed Perforated Plate Inserts, Appl. Energy J., 136 (2014), Dec., pp. 989-1003
- [14] Li, L. D., et al., Vacuum Reliability Analysis of Parabolic Trough Receiver, Sol. Energy Mater Sol. Cells., 105 (2012), Oct., pp. 302-308
- [15] Liu, L.Q., Lei, J. D., Vacuum Lifetime and Residual Gas Analysis of Parabolic Trough Receiver, *Renew Energy.*, 86 (2016), Feb., pp. 949-954
- [16] Lei, W. Z., et al., Experimental Study of Glass to Metal Seals for Parabolic Trough Receivers, Renew Energy., 48 (2012), Dec., pp. 85-91
- [17] Wu, Z, L., et al., Three-Dimensional Numerical Study of Heat Transfer Characteristics of Parabolic trough Receiver, Applied Energy, 113 (2014), Jan., pp. 902-911
- [18] Zhang, L., et al., An Experimental Investigation of a Natural Circulation Heat Pipe System Applied to a Parabolic Trough Solar Collector Steam Generation System, Sol. Energy, 86 (2012), 3, pp. 911-919
- [19] Rolim, M. M., et al., Analytic Modeling of a Solar Power Plant with Parabolic Linear Collectors, Sol. Energy, 83 (2009), 1, pp. 126-133
- [20] Dudley, V., et al., Test Results: SEGS LS-2 Solar Collector, SAND 94-1884. Sandia National Laboratories, Albuquerque, N. Mex., USA, 1994
- [21] Padilla, R. V., et al., Heat Transfer Analysis of Parabolic Trough Solar Receiver, Appl. Energy, 88 (2011), 12, pp. 5097-5110
- [22] de A. R. Vinuesa, et al., Simulations and Experiments of Heat Loss from a Parabolic Trough Absorber Tube over a Range of Pressures and Gas Compositions in the Vacuum Chamber, J. Renew. Sustain. Energy, 8 (2016), 2, pp. 23701-16

- [23] Forristali, R., Heat Transfer Analysis and Modeling of a Parabolic trough Solar Receiver Implemented in Engineering Equation Solver, Technical Report NREL/TP 550-34169, National Renewable Energy Lab., Golden, Cal., USA, 2003
- [24] Gutierrez-Trashorras, A. J., et al., Attenuation Processes of Solar Radiation, Application to the Quantification of Direct and Diffuse Solar Irradiances on Horizontal Surfaces in Mexico by Means of an Overall Atmospheric Transmittance, *Renewable and Sustainable Energy Reviews*, 81 (2018), Part 1, pp. 93-106
- [25] Chen, J. L., et al., Study for the Irradiance Attenuation on the Cover of Solar, Collectors Due to Humidity and Dustall in Southerm Taiwan, Energy Procedia, 118 (2011), Aug., pp. 79-87
- [26] Williams, N. McAdams, *Heat Transmission*, McGraw-Hill, New York, USA, 3<sup>rd</sup> edition, No. 660.28427 M32., 1954

Paper submitted: August 30, 2017 Paper revised: February 19, 2018 Paper accepted: March 20, 2018 © 2019 Society of Thermal Engineers of Serbia Published by the Vinča Institute of Nuclear Sciences, Belgrade, Serbia. This is an open access article distributed under the CC BY-NC-ND 4.0 terms and conditions