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Investigation of Solar Cycloidal Concentrating System Using Variable Concentration Ratio

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Abstract
In this paper investigations are made by using cycloidal concentrating system with receiver having variable concentration ratio. For comparison purpose investigations are done by using receivers having constant concentration ratio and having 0.038 m, 0.031m and 0.025 m diameters from application point of view. System performance were carried out using theoretical evaluation. For this equation of energy balance and modes of heat transfer are utilized. For the analytical study various correlations are used. Efficiency obtained by using theoretical analysis matches with the results obtained by using experimental analysis and hence validated. Design considerations are elaborated used in research. The present research represents points like correlation between concentration ratio and intercepts factor effect of receiver temperature on efficiency, effect of concentration ratio on temperature difference at that incident beam radiation and effective increase in efficiency using variable concentration ratio. Author has registered and received the copyrights for the said design. Author has filed and published a Patent having Patent No.202021028009A on 31st July 20 for which FER of patent is also accepted by the Govt.of India.
Keywords: *Investigation, variable ratio, solar energy, design factors, energy*

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I. Preamble

Utilization of solar energy to heat the water has wide applications in industrial and domestic life. But efficiency obtained by using solar system and temperature obtained by using it has some problems which need enhancement. In existing parabolic system constant concentration ratio is used, leading to high heat loss. Hence there is a need to investigate the system where heat loss is reduced. In proposed solar thermal concentrating system attempts are made to improve the efficiency and minimize the heat loss. The existing system can be changed by using proposed solutions considering economy point of view.

II. Literature review

Firdaus Muhammad-ski et.al [1] carried out research on solar reflector and mentioned that from other design there is still a lot of scope for development when it comes to the design of the concentrator. Ricardo et al. [2] carried out study with a PTC. Transparent cover is used on the receiver. Due to this heat loss is avoided. Xian-long et al. [3] carried out study with CCPC. CCPC has been found to offer greater efficiency throughout the day. P. Horta et al. [4] conducted research using simulation and not the experimentation. Lof et al. [5] tried to optimize the reflector design by conducting research related to concentrator area to the receiver area. In this study, a receiver with flat cross-section used in which effect of shadow was not considered. P. Beucherie [6] Khaled Mahdi et.al [7] carried out investigations with a cylindrical receiver and a spherical concentrator. Relationship between intercept factor and receiver diameter was studied here. Therefore, care must be taken to increase the concentration ratio. Simon Caron et al [8] presented a receiver design having modified heat transfer features. Matthew Roselle et.al [9] carried out research to know the system performance and stated that system efficiency will decreases when diameter of receiver decreases. Eckhard et.al [10] studied position of receiver in regards with line of focus creates influence on intercept factor. After identification of research findings in the existing solar concentrating system like orientation of surface, geometrical parameters, receiver position, angle of rim, receiver shape, selection of material author has proposed the concept of novel solar cycloidal concentrating system with variable concentration ratio as an application and design studies point of view. Table 1 shows nomenclature used this research paper. Table 2 shows application where proposed solar system can be used for mid-range temperature purpose.

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Table 1. Nomenclature

Nomenclature	Symbol	Unit
Receiver circumference	L1	M
Inlet and outlet temperature	Tin and Toot	K
Coefficient of Friction	h_c	W/m^2°C
Concentrator length	L	M
Receiver temperature	t_r	°C
Convectional heat losses	Qc	W
Receiver surface temperature	Tr	K
Surrounding Temperature	t_a	°C
Average Temperature	T_m	K
Diff.in Temp.	ΔT	K
Incident beam radiation	$_{Ib}$	W/m^2°C
Grashoff no.	G_r	-
Prandtl no.	P_r	-
Nusselt no.	Nu	-
Specific heat	Cp	kJ/kg/°C

Table 2 Industrial processes with temperature range [12]

Industrial sector	App.	Temp. Range (^{0}C)
Food	Drying process	40-80
	Washing process	50-90
	Pasteurizing process	50-80
	Boil	70-95
	Sterilize	80-110
	Heating	45-65
Beverages	Washing process	65-80
	Sterilize	60-85
	Pasteurize	60 – 75
Paper Industry	Paper feeding	60 – 88
	Water feeding	50 – 80
	Bleach	70-100
Textile Industry	Bleach	60 -90
	Dyeing process	70 – 90
	Degreasing	90-110
	Washing process	45-60

2.1 Research gap/findings and research contribution

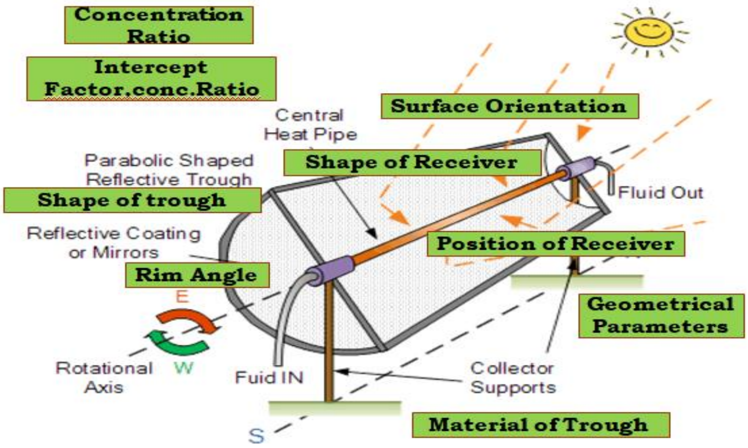


Figure.1 showing scope for Research work in existing parabolic concentrating system [11]

Figure 1 shows scope for research work in existing Parabolic concentrating system where,

- To ensure that sunlight reaches the system's surface, it is crucial to take the orientation of the surface into account. In the proposed system, the receiver moves while the concentrator is placed with its axis in the east-west direction and the surface facing 18.5 south (Pune's latitude).
- Parameters related with geometry of system like aperture width, concentrator length need to be select for achieving the appropriate line of focus.
- Proper selection of receiver position for desired flux distribution received from collector.
- Angle of rim selected to reduce the variation in rays coming from reflector.

- Receiver shape selected to enhance the efficiency by reducing the heat losses.
- Material selection for the structure of concentrating system.

Based on above research finding author has proposed this system.

2.2 Problem Statement and research objectives
Statement: Design and develop a solar cycloid concentrator system with a variable concentration ratio to improve system efficiency.
Objectives:

- Analysis of the effectiveness of a solar concentration system by examining a cycloid solar concentration system with a variable concentration ratio.
- To find out the correlation between the intercept factor and the concentration ratio.
- Design and evaluation of the effectiveness of a variable concentration ratio receiver.
- Validate the results experimentally.

III. Design consideration

3.1 Construction of the system
Constructional details are as shown in Fig.2 and Table 3 shows design specification in the preparation experimental set up.

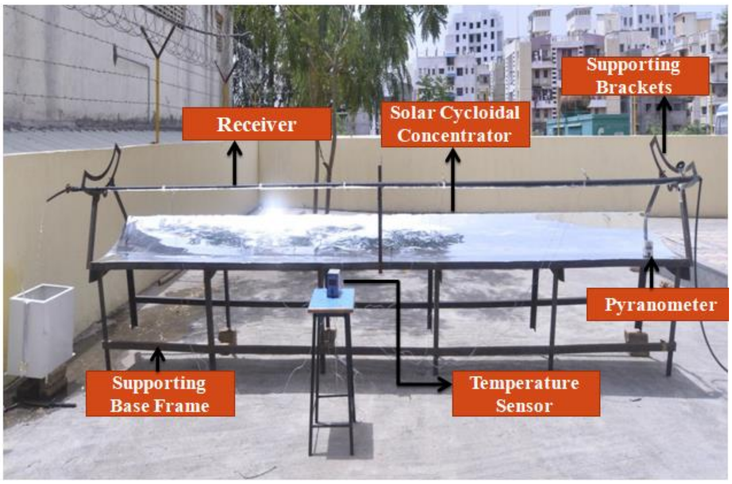


Figure 2 Experimental set up of the solar cycloidal concentrator [13]

Table No.3 Design specifications [14]

Design consideration	Value	Assumption	Value
Collector Aperture	0.6m	I_b	600 W/m^2
Collector Length	6m	P	0.95
Rim Angle	47^0	α	0.8
Focal Distance	0.375m	ϒ	0.8
Receiver Diameter	Variable		
Concentration Ratio	Variable		
Water Flow Rate	controlled by control valve, flow meter,0.00833		
Storage Tank Capacity	50 lit.		
Concentrator Diameter	0.375*2*2*II =4.71		

Here concentrator is stable and receiver is moving. Concentrator is orientated in east –west direction with 18.5^0 south latitude. Due to this orientation solar rays were directly incident on trough. These rays reflect back to the receiver. Receiver is mounted in line with line of focus.. Intention behind this is to obtain maximum flux distribution on receiver. Working fluid is water. It flows from inlet to outlet. Flow control valves are used at both the ends. Temperature is measured using thermometer. Flux is measured using sun meter. Fig.2 shows experimental set up while Fig.3 shows position of summer solstice.

3.2 Selection of geometrical parameter for concentrator

Geometrical parameters affect the system performance. Solar flux enters through the aperture. Here it is referred as concentrator width. In this research 6m long trough with 0.6 m width of aperture was used. There is limitation to increase trough length as focal line may shift upwards and hence tracking of flux becomes difficult. These parameters also affect system economy.

3.3 Aperture Area

Through this area solar radiations enters in to the trough. Here trough length is 6m and width 0.6m was used. Thus opening area is $3.6m^2$.

3.4 Selection of Rim Angle

It is the angle between lines, the line connecting the position of the sun reflector center to the circle center. Changing the rim angle results in a different flow distribution. If arc varies then its focus also varies. Here, concentration system with E-W orientation was used. Considering sun movement 47^0 from N-S an angle of 23.5^0 chosen. Hence arc becomes 47^0. With respect to motion of sun, latitude also changes. Figure 3 shows path of the receiver showing rim angle based on position of summer solstice.

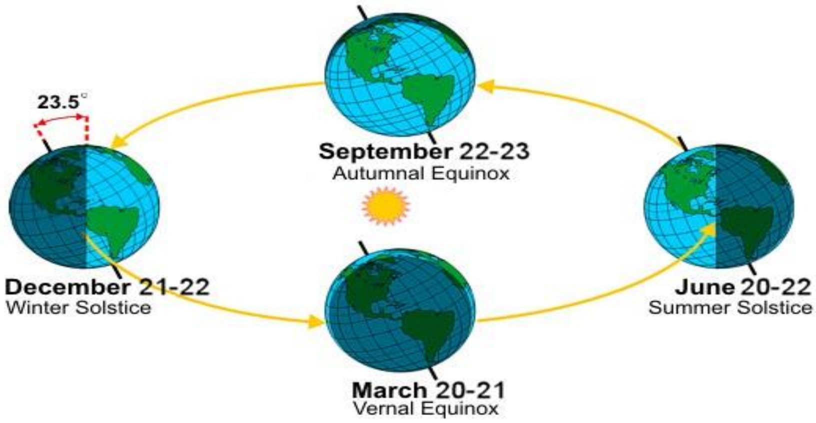


Figure 3 Position of summer solstice [15]

Actually, the sun moves from east to west at a constant speed of 15^0 per hour. During the year the Sun undergoes direct consonant movement through 46.9^0 (about 47^0) in the N-S position. This movement is an important basis for the use of east-west concentrators.

3.5 Length of the Trough

Length of trough is decided as 6m for experimental purpose. The selection of the receiver length depends on inlet temperature and flow rate of the fluid. With the data available and theoretical inputs, the present setup was finalized. The usual ratio for the length to the aperture is 10 for experimental concentrators. As width of aperture is 0.6 and length of trough is 6m so, it will fulfill this criterion.

3.6 Selection of Optical Parameter for Concentrator

It is expressed as,

$$\eta = \rho\, \alpha\, \gamma \qquad (1)$$

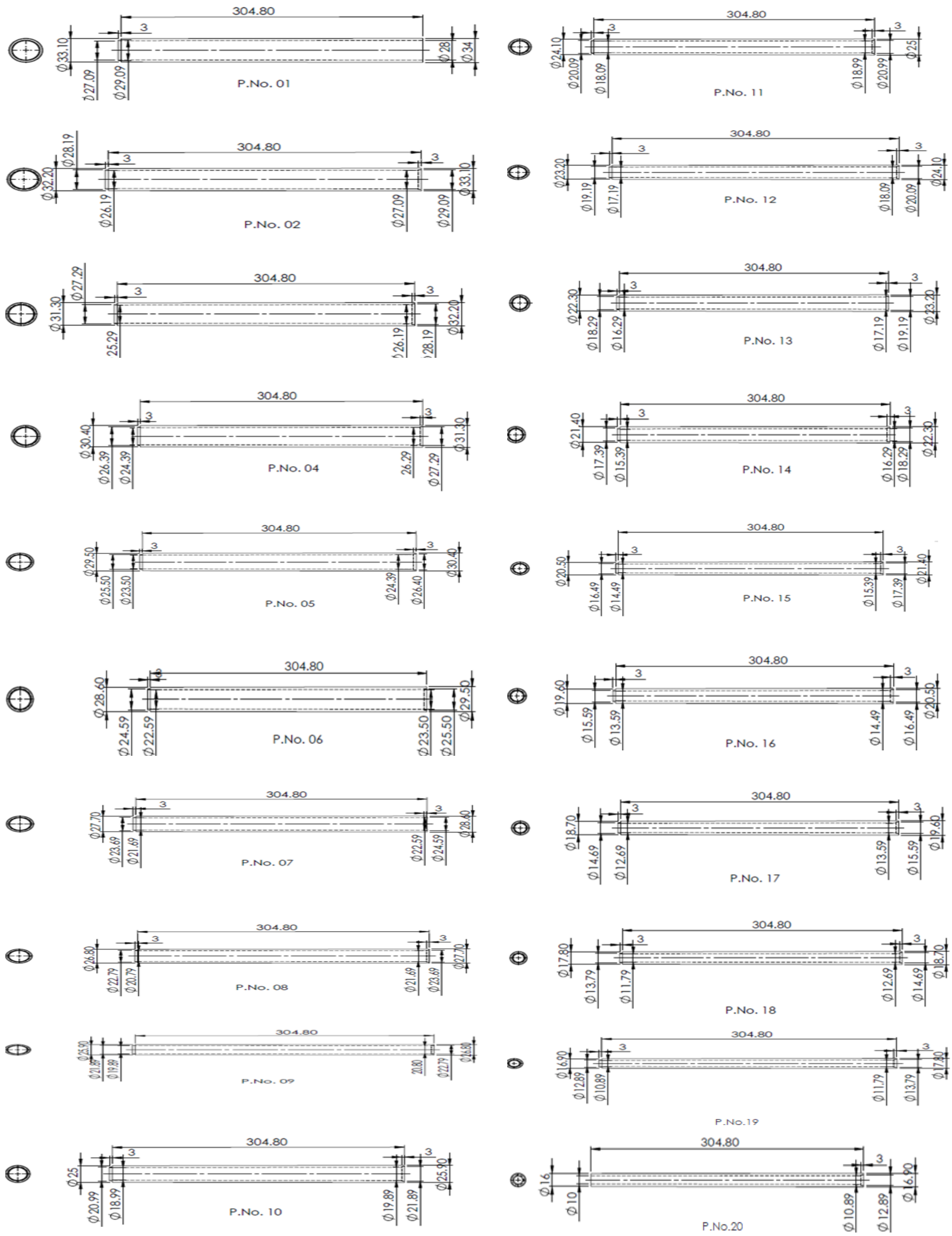
Optical efficiency is directly proportional to the reflectivity and absorptivity. Here 0.95 reflectivity was considered based on manufacturing specifications.

3.7 Trough manufacturing

Careful attention is paid during manufacture so that trough remain cycloidal. Care has been taken to avoid bending of trough which cause sagging along its length. A support surface of 1.5mm thick GI sheet metal is spot welded over these circular supports. The actual reflective surface consists of Alanoid sheet made by Alanoid, Germany. As per manufacturing specifications, the reflectivity of the surface is 0.95.

3.8 Receiver Assembly with variable concentration ratio

Fig.4 Detailed design of 20Pieces of Tapered Receiver [13]



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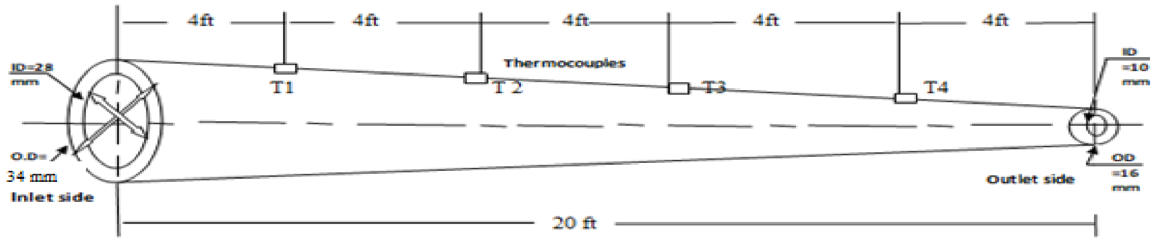

Fig. 5 Detailed design of 20 pieces of tapered receiver [13]

The shape of the receiver is conical to compensate thermal losses. Black color coating was done on receiver. for the receiver was chosen to have a lower manufacturing cost than others. Fig.5 shows detailed assembly of receiver. Manufacturing the receiver involves various operations such as bar cutting, turning, arc welding, attaching thermocouples according to the design, and attaching nozzles to the end of the receiver. The entire 20-foot bar is cut into twenty-one foot pieces and fabricated using CNC and machining operations. The detailed construction of each 20 parts for the production of the conical rod is shown in Fig. 4. The construction of the conical receiver and the assembly of the thermocouples is shown in Fig. 5.

IV. Theoretical analysis

4.1 Energy balance equation

Figure 6 shows balance of energy in proposed system. Incident beam radiations are measured by using sun meter.

$$\text{Energy across the aperture } E_A = I_b . A \qquad (2)$$

Reflectivity of the system is expressed as,

$$\text{Energy reflected by the concentrator } E_R = I_b . A . \rho \quad (3)$$

Incident beam radiations are measured by sun meter. Energy intercepted by receiver is expressed as,

$$I_b(\text{by receiver}) = I_b A \ \rho \, \alpha \, \Upsilon \qquad (4)$$

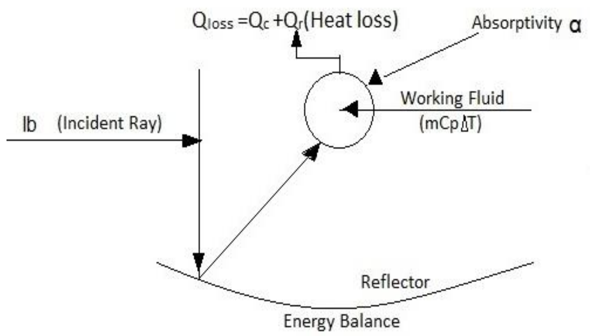

Figure 6. Balance of energy in proposed system [13]

Equation of energy balance is presented as,

$$m_w C_P \Delta T1 = I_b A \, \rho\alpha\Upsilon - (Q_C + Q_r) \qquad (5)$$

4.2 Governing equations

Heat loss due to convection is expressed as,

$$Q_C = h_c \Pi \, d \, L \, (T_r - Ta) \qquad (6)$$

Radiative heat loss Qr is calculated using the following formula,

$$Q_r = \epsilon \, \sigma \, \Pi \, d \, L \, (T_r^4 - T_{sky}^4) \qquad (7)$$

Heat transfer coefficient (hc) is calculated as,

$$h_c = \frac{N_u}{L} \qquad (8)$$

Nusselt number is determined as,

$$Nu = \left\{0.60 + 0.387 R_a^{\frac{1}{6}}\left[1 + \left[\frac{0.559}{P_r}\right]^{\frac{9}{16}}\right]^{\frac{-8}{27}}\right\}^2 \quad (9)$$

Where, $R_a = G_r . P_r$ (10)

The Grashhoff no.is calculated as,

$$Gr = \frac{L^3 g_c \beta \Delta T}{\vartheta^2} \quad (11)$$

4.3 Theoretical efficiency

By using all above expressions for receiver with variable concentration ratio, convective loss and radiation loss is evaluated.

$$Q_{gain} = I_b A \rho \alpha \gamma - (Q_C + Q_r) \quad (12)$$

$$\eta = \frac{Q_{gain}}{\text{Energy across the Receiver}} \quad (13)$$

$$\eta = \frac{Q_{gain}}{I_b A} \quad (14)$$

$$\eta = \frac{I_b A \rho \alpha \gamma - (Q_C + Q_r)}{I_b A} \quad (15)$$

The evaluated theoretical efficiency of cycloidal concentrator for receiver having variable concentration ratio at 50°C receiver surface temperature is 0.53%.

V. Experimental analysis

5.1 Experimentation

Investigation of research with respect to experimental set up was conducted using three receivers (0.038 m, 0.031 m, 0.025 m) and receiver with variable concentration ratio using experimental set up as shown in Figure 2. Configuration of experimental set up is as shown in Figure 2. The efficiency obtained after experimentation of the designed and developed solar cycloidal line concentrator expressed as,

$$\eta = \frac{m_w c_p (T_2 - T_1)}{I_b * A} \quad (16)$$

The experimental efficiency of the designed and developed solar cycloidal line concentrator at 12.30 pm for receiver having variable concentration ratio is 0.51% hence these results are similar to theoretical analysis results and hence validated.

VI. Result and discussion

Theoretical evaluation was done based on proposed concept and system performance was also determined. Further, the experimental set up was developed and the corresponding experiments as per the requirement for validating the theoretical concept were carried out. The presented data provides the results of theoretical and experimental work carried out. Also, it elaborates upon the probable causes for the designed system performance.

6.1 Connection between Intercept factor and Receiver diameter

After theoretical evaluation followed by experimental and testing of solar system, relationship is as shown in Fig.7.

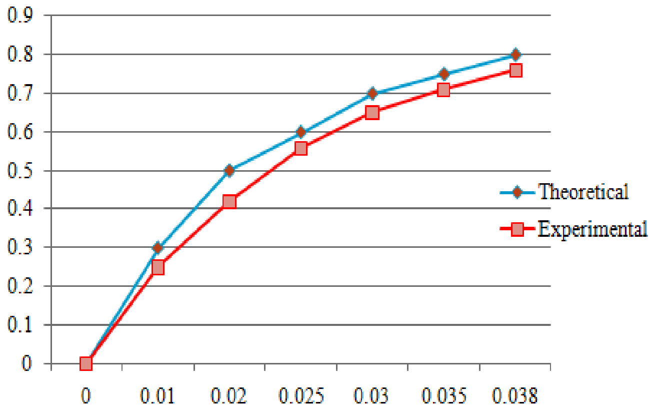

Figure 7 Relation between receiver diameter and Intercept Factor. [13]

Figure 7 shows that the intercept factor increases as the receiver diameter increases, which imply the inverse proportionality between concentration ratio and intercept factor. However, this is not a linear relationship. The results obtained related with these two parameters further supports to use variable concentration ratio for efficiency improvement by reducing heat losses.

6.2 Effect of receiver surface temperature on efficiency

Temperature of the receiver surface affects temperature of working fluid followed by system efficiency. It is shown in Figure 8 below.

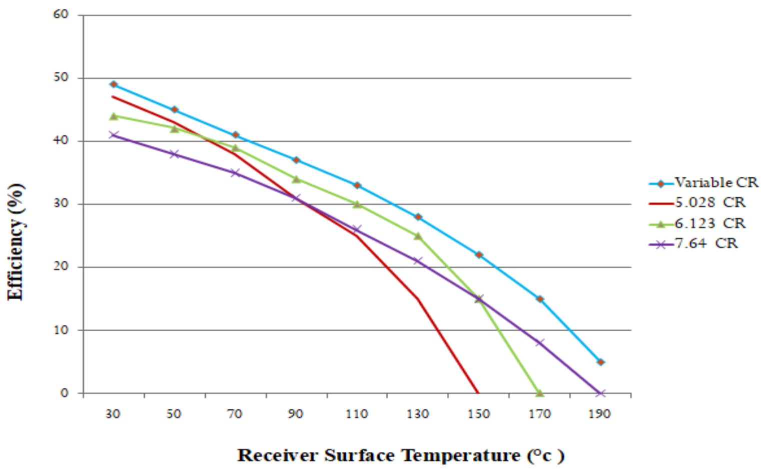

Fig. 8 Efficiency Vs temperature [13]

Figure 8 indicates that as surface temperature of the receiver's increases, losses due to conduction and radiation also increases. Due to this efficiency decreases. For the receiver having low CR fall of efficiency is higher. But in case of receiver having variable CR fall of efficiency is less. As compared with other systems higher temperature was also received. After experiments, the results show that changing the concentration ratio by using a variable concentration ratio has an effect on the surface temperature of the receiver.

6.3 Effect of concentration ratio on $\Delta T/I_b$ and efficiency

The performance measure of the solar line concentrator is adjudged by the obtained efficiency with respect to the temperature attained by the working fluid in Figure 9, 10, 11 and Fig 12. It depicts the nature of the performance (efficiency) with respect to the temperature difference of the working fluid at actual incidence beam radiation on given reflector for system of various Concentration Ratios.

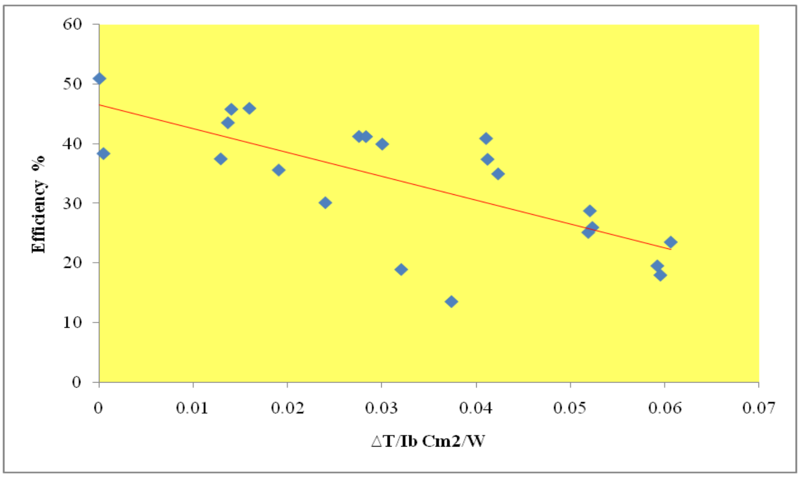

Figure 9 Efficiency curve for cycloidal line concentrator with CR 5.028

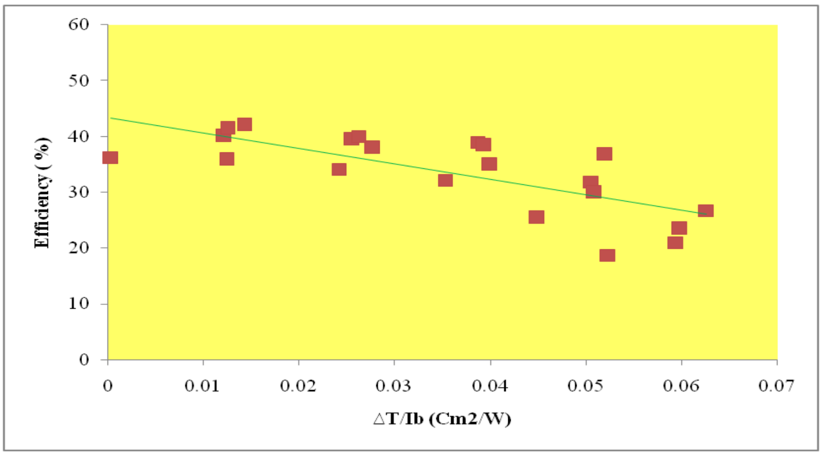

Figure 10 Efficiency curve for cycloidal line concentrator with CR 6.123

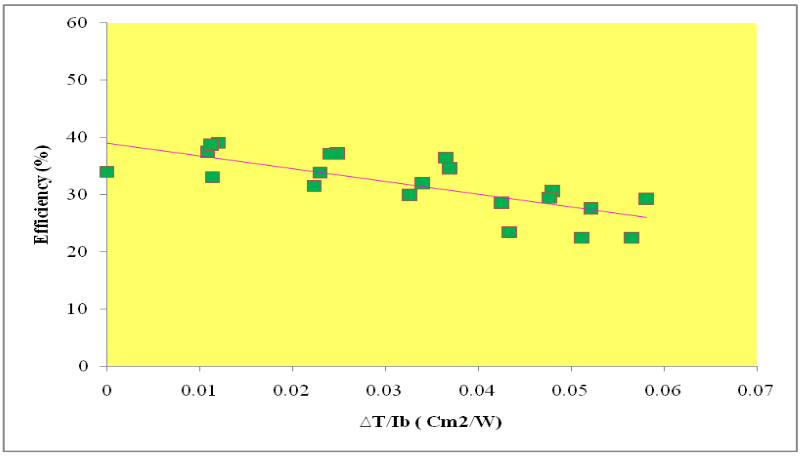

Figure 11 Efficiency curve for cycloidal line concentrator with CR 7.64

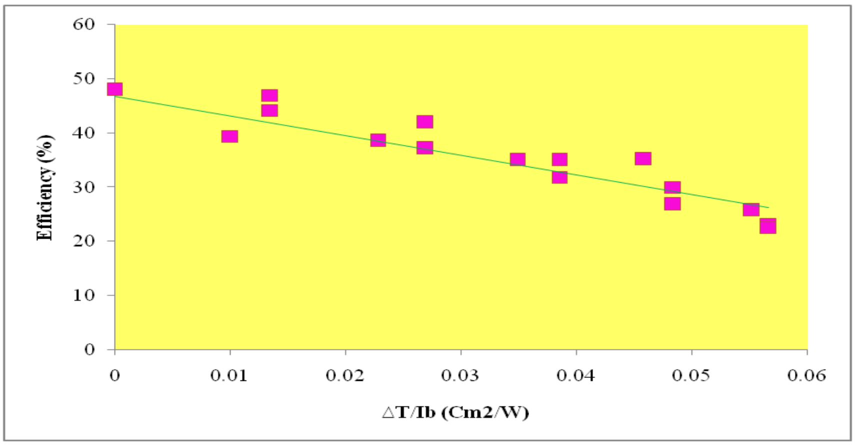

Figure 12 Efficiency Curve for Cycloidal line concentrator with variable CR

It is observed from the figures that as the concentration ratio increases the efficiency obtained for the particular temperature difference decreases. Convective and radiative heat losses contribute to the total loss. Convective heat loss depends on the convective heat transfer coefficient and increases with increasing receiver temperature. Similarly, as the receiver temperature increases, radiative losses increase. However, it is to be noted that the performance trend observed for all the receivers is similar in nature, which is in confirmation with the earlier published results for Parabolic Trough Concentrator. It is to be noted that the overall efficiency obtained from the system with variable concentration ratio is high as compared with the system having a uniform concentration ratio. This is due to the obtained higher temperature difference of working fluid. However, in case of the system with variable concentration ratio, the temperature difference obtained at a particular location of the receiver is high and the obtained efficiency is also high as per the expectation.

VII. Conclusion

In proposed research investigations novel concept about solar cycloidal concentrating system along with consistent variable concentration ratio is presented. The concluding remarks are presented as,

1. With reference to results obtained it is observed that, with a constant CR of 7.64, the efficiency of concentrator is 39% and outlet temperature is 72ºC, while, with variable C.R. the efficiency of concentrator 51% and outlet temperature of water is 98ºC.The increase in efficiency is 12% and the % gain in efficiency is 30%.
2. It is to be noted that the overall efficiency obtained from the system with variable CR is high as compared with the system having a uniform Concentration Ratio. This is due to the obtained higher temperature difference of working fluid. However, in case of the system with variable CR, the temperature difference obtained at a particular location of the receiver is high and the obtained efficiency is also high as per the expectation.
3. It is proved from the research of comparative investigation that as intercept factor increases, concentration ratio decreases. In present research for receiver having diameter 0.038m, concentration ratio is 5.028 and intercept factor is 0.8. While for receiver having 0.031m diameter, concentration ratio is 6.123 and intercept factor is 0.7 and for diameter having0.025m, CR is 7.64 and intercept factor is 0.6.
4. In proposed research, diameter of receiver continuously varying from inlet to outlet. Thermal losses are very less as compared with constant CR. When diameter of receiver is constant from inlet to outlet, thermal or heat loss is also higher as receiver area increases, they also increase.
5. It is to be noted that the overall efficiency obtained from the system with variable concentration ratio is high as compared with the system having a uniform concentration ratio.
6. The presented solar cycloidal concentrating system is easy to manufacture and found economical as compared to the existing parabolic system. Achieving line of focus for getting highest intensity of reflected rays is easier in this type of solar concentrating system.
7. The novel concept of using stationary solar cycloidal concentrating system and with variable concentration ratio for which Patent and copyrights are received, receiver is moving and solar system is stationary. Due to this arrangement, tracking of receiver either by manual or automatic means for capturing concentrated solar rays at focal line becomes easy.
8. The proposed solar cycloidal concentrating system with variable concentration ratio offers additional advantage of reduced cost of tracking, maximum solar ray reflection and becomes useful for midrange temperature range.

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