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Design and Development of receiver for utilization of concentrated solar power

[1]Pradeep Reddy Anna Reddy
School of Mechanical and Building Sciences, VIT University, Vellore, India

Abstract: **A theoretical analysis is done on a single unit parabolic trough collector with different specifications of the receiver tube. Since parabolic trough collector is an important concentrated solar power technology, the aim is to do theoretical thermal performance of receiver with different specifications and theoretical final performances of the collector are compared with each other respectively and the best specification is used for fabrication and testing. The theoretical results show that the SiC material results better than SS304 and therminal VP-1 is better than water for using as a heat transfer fluid. The best specification obtained to use is silicon carbide and therminal VP-1 with 36 mm outer diameter tube when 3 kg/min fluid flow is maintained, it reaches 370 °C.**

Keywords: **Concentrated solar power, parabolic trough collector, receiver and heat transfer fluid.**

I. Introduction

The increase in demand for energy consumption across the globe is forcing the energy sectors to go for renewable energy sources and their respective technologies to utilize them. Concentrated solar power (CSP) technologies are getting more prominent than solar PV panels and wind power technologies. Parabolic trough collectors, the most successful technology than the solar towers (HFC), Linear Fresnel collectors (LFC) and parabolic dishes (PDC) because of its easy mechanism, modelling, installation and operation of the technology respective to others. Studies show that parabolic troughs have more installed, under construction and planning phase capacities of power plants than the other concentrated solar power technologies. Here, in the study parabolic troughs are studied and considered a closed parabolic trough by covering at the both ends of reflector by reflector material and top of reflector with glass to avoid wind losses and perform calculations. The theoretical performances are calculated with different specifications of receiver and the better receiver specification is suggested which have better utilization of concentrated solar power. [1], [2]

II. PARABOLIC TROUGH COLLECTORS

Parabolic trough collector consists of a parabolic profile reflector with certain rim angle and respective focal line where the receiver is placed. It is generally operated by using tracking system and is a single axis tracking mechanism. Using of tracking system benefits in capturing maximum amount of solar radiations. This technology is the most matured and even it is easy for making small units for experimenting and analyzing.

[1]***A.Pradeep Reddy***, M.TECH, Energy and Environmental Engineering, SMBS, VIT- University, Vellore, Tamil Nadu, India-632014

The statistics of concentrated solar power projects by end of year 2010 shows that, around 90% of the capacities are parabolic trough collectors which are clearly more than other three concentrated solar power technologies. [18]

TABLE I
CSP PROJECTS IN 2010 ACROSS THE GLOBE IN GW

Type	**Operational**	**Under construction**	**Planning phase**
HFC	0.044	0.017	1.603
PDC	0.002	0.001	2.247
LFR	0.009	0.030	0.134
PTC	0.778	1.400	8.144

Parabolic trough collector has five major components, which are receiver, reflector, heat transfer fluid, tracking system and support structure. The performance of the collector mainly depends on the receiver and heat transfer fluid. The reflector, tracking system and support structure also plays an important like, the reflector with good reflectivity and less absorptivity can reflect more radiations on to the receiver and tracking system allows the whole collector to rotate along with the suns path so that radiation fall on the reflector most of time and also the support structure helps in preventing the reflector from deforming its shape as well rotating the reflector evenly along its length. [3], [5]

A. Receiver

Receiver is a component where the reflected radiations from the reflectors are focused and high temperatures are attained due to concentrated radiations. And then heat gained is utilized for the production of steam for electricity generation or for thermal applications.

The Parabolic troughs mainly use Omni-directional receivers which are also known as external receivers. There is one another type of receiver known as cavity receiver which is not suitable for parabolic troughs. Non-insulated low-temperature receiver, this is a simple metal tube, painted black or covered by a selective absorption layer. It is the most economic receiver and also suitable for conducting experiments and analyzing performance by making modifications to the collector. Photovoltaic receiver is a metal tube covered at the outside by a layer of photovoltaic cells. When put under the focus, the photovoltaic cells receive concentrated light and generate electricity with a much higher output rate than non-concentrated cells. But this model is expensive and complicated.

B. Tracking

The trough is usually aligned on a north-south axis, and rotated to track the sun as it moves across the sky. Alternatively the trough can be aligned on an east-west axis which is not effective compared to the other alignment. Trough should be provided to a tracking system for easy operation because usually sun rotates 15 degrees every 1 hour, and because of the sun's rotation the collector could not receive the direct radiations all the time. Different types of tracking system are available depending on the collector equipment dimensions which usually work on slewing drive. Energy lost can be defined in cosine.
Power lost = 1 – cosine [I], where I is the angle rotated by the sun from initial point.

C. Heat Transfer Fluid

Heat transfer fluid is for absorbing the heat from receiver and this is used either by transferring the heat to other medium or by using direct applications. Molten salt, water and some synthetic oils are used as heat transfer fluids. Water is generally used in the case of direct heat generating systems and also it is not applicable in all situations as it is having low boiling point compared to other heat transfer fluids. Therminol vp1 is the common fluid used as a heat transfer fluid because of its feasible thermal properties which are suitable for using as a heat transfer fluid.

D. Receiver Materials

Receiver materials should have good heat absorption rates and heat transfer ability. Different materials can be used as receiver material depending upon their thermal properties and usually material is selected by choosing its cost according to the fabricating system.

1) SS304

Stainless Steel commonly known as SS, have many types of SS grades. Among them grade SS304 is the standard "18/8" (18% Chromium and 8% nickel) austenitic stainless. SS304 properties: Density- 7900 Kg/m³, Thermal conductivity- at 100°C is 16.3 W/m-K and at 500°C is 21.5 W/m-K, Melting point is 1400°C-1450°C and Specific heat between 0-100°C is 0.5 Kj/Kg-K.

2) SS316

Grade 316 is the standard molybdenum-bearing austenitic grade, most preferred stainless steel after 304. The molybdenum gives 316 better overall corrosion resistant properties, particularly higher resistance. This grade of SS is more corrosion resistant than the SS304. SS316 properties: Density- 8000 Kg/m³, Thermal conductivity- at 100°C is 16.3 W/m-K and at 500°C is 21.5 W/m-K, Melting point is 1375°C-1400° and Specific heat between 0-100°C is 0.5 Kj/Kg-K.J

3) Silicon Carbide- SiC

Silicon Carbide is the only chemical compound of carbon and silicon. It was originally produced by a high temperature electro-chemical reaction of sand and carbon. Silicon carbide is an excellent abrasive. Silicon carbide ceramics with little or no grain boundary impurities maintain their strength to very high temperatures, approaching 1600°C with no strength loss. SiC properties: Density- 3100-3210 Kg/m³, Thermal conductivity- at 20°C is 120 W/m-K, Melting point is 2730°C and Specific heat 20°C is 0.75 Kj/Kg-K. SiC loses its strength when it reaches above 1600°C.

4) Aluminium

Aluminium is an excellent heat and electricity conductor and in relation to its weight is almost twice as good a conductor as copper. Aluminium properties: Density- 2700-2900 Kg/m³, Thermal conductivity- 237 W/m-K, Melting point is 660°C and Specific heat at 20°C is 0.944 Kj/Kg-K.

5) Copper

Copper is having very high thermal and electrical conductivity. This is the reason why copper has been used mostly in electrical and electronic devices. But copper is an expensive metal. Copper properties: Density-8960 Kg/m³, Thermal conductivity- 401 W/m-K, Melting point is 1084°C and Specific heat at 20°C is 0.39 Kj/Kg-K.

6) Selective Coatings

Selective coatings should have good solar absorption rates and low thermal emissivity. Some of the selective coatings are Black Chrome, Black nickel, Aluminium oxide with Nickel and Titanium-Nitride-Oxide Layer. Black Chrome is favourable coating because of its high spectral selectivity and high durability. Black paint have good absorption rate and can be used as coating but it is also having high thermal emissivity which makes it non applicable as selective coating. The suitable values for selective coating might be 0.9 of solar absorption and 0.10 of thermal emissivity.

E. Heat Transfer In Receiver

- First, the receiver outer surface will absorb the solar irradiation which incidents on it through the reflector. This process is done by radiation. If the concentration ratio is high, the intensity of the energy received on the receiver is more.
- Concentration ratio is the effective aperture area of the reflector/collector to the absorber/receiver area.
- In case of receiver tube without any glass cover the energy received by the tube on the outer surface will transfer into the inner surface through conduction heat transfer. And this depends on the thermal conducting properties of the material.

- The fluid medium that passes through the receiver will be absorbing energy from receiver through the convection heat transfer. The heat transfer rate depends on the flow rate of the medium and also the convective heat transfer co-efficient.
- In case of glass envelope, the energy is again transmitted from glass envelope inner surface to the outer surface of the tube through radiation heat transfer which depends on the emitting property of the glass envelope. Earlier the energy is transferred from the glass envelope outer surface to inner surface by conduction process.
- There will be heat losses through the outer surfaces of tube or glass envelope because of the radiation and convection heat transfers.
- The wind flow around the receiver will result in the convection heat loss and because of the emitting properties of the receiver material.
- The surface temperature of the receiver tube depends on the mass of the tube. The mass of the receiver tube increases as the thickness and length of the tube increases.
- For the same energy availability as the mass of the tube increases the energy distribution will be more which results in decrease in surface temperature. And as the mass of receiver is low the temperature will be higher.[12], [15], [16]

III. THEORETICAL ANALYSIS

The Parabolic trough collector has concentration ratio between 15 to 45 and the operating temperatures between 50 to 400°C generally. Since it is a single axis mechanism and line focussed, concentration and operating temperatures are low compared to other technologies. Mainly Evacuated tubes are used in the parabolic trough collector as receiver, this tubes have a glass cover around the tube where generally medium is vacuum. This makes the convection losses reduced from tube as mentioned earlier in receiver heat transfer. Here the specifications of the receiver are been changed so that different performances can be achieved and the best specification can be decided for fabricating the system and experimenting in further process. General layout of the parabolic trough collector is shown below.

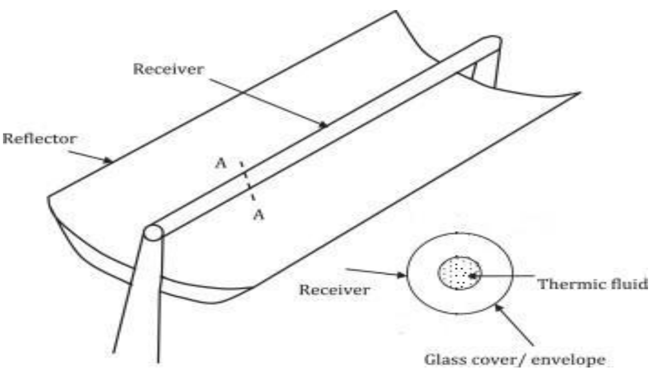

Figure 1: Parabolic trough collector line model with parts

The receiver generally used is evacuated tube collector as mentioned before. Now, the performance of the collector is calculated when receiver is replaced with a normal tube which is coated with a selective coating with good absorptivity.

The trough dimensions are considered as a 4 meter length and 2 meter wide. The receiver length is 4 meter and different dimensions of the outside diameter of the tube are considered like 73 mm, 36 mm, 23 mm, 18 mm, 14 mm and 12mm. Two materials Silicon Carbide and Stainless Steel grade SS316 are used for calculating the performances. The other materials mentioned above can also be used but these two materials are considered to be better one regarding the cost and silicon carbide because of its ceramic thermal properties.

The receiver specification when it is 73 mm outer diameter a single tube is considered and when the diameter of receiver is reduced it is considered as number of tubes used in the receiver is increased that is if the receiver diameter is 36 mm then two tubes which are connected with each other so that one end of the tube is inlet and the other end of the tube is connected to the second tube and the other end of the second tube as outlet. Likewise when diameters of the tube are 23 mm, 18 mm, 14 mm and 12 mm, the number of tubes used are 3, 4, 5 and 6 respectively.

For both the materials using in the calculations the respective tube diameters are considered as an option for comparing the specification while both water and therminal VP1 used as heat transfer fluids. Solar conditions are considered as of Bengaluru co-ordinates 12°58 north, 77°34 east, is having annual average of solar irradiation 5.26 Kw-hr/m²-day. Considering, the reflector material as SS316 supported by the mild steel structure. And also assuming both ends of reflector are covered by the reflector material for reducing the radiation losses. Even the top of reflector is covered by the glass which is having good transmissivity it is because of getting rid of wind losses. [10], [11]

A. Energy Availability

Energy incident on the receiver tube is calculated by multiplying the solar radiation available for certain amount of duration, reflector area and loss factors which affects the loss of radiations. Loss factors which included are reflectivity of the reflector material, absorptivity of the reflector, emissivity of the reflector, transmissivity of the glass which is covered over the reflector. This makes the parabolic trough collector as closed as the both ends and top of the reflector are covered.

B. Surface Temperature (Receiver)

Receiver surface temperature is calculated by the energy gain formula $Q=m^* C_p *(T_s-T_i)$

Where, Q = Energy available (joules),

m = Mass of the receiver material (grams),

C_P = Specific heat of the receiver material (joule/gram- °C),

T_I = Initial temperature of receiver material (°C),

T_S = Final surface temperature of receiver (°C).

C. Exit Fluid Temperature

Exit fluid temperature is calculated from the formula constant surface temperature in a tube, here surface temperature is assumed to be constant though the surface temperature is not constant for simplicity of calculations. [22]

$T_E = ((T_I - T_S) * e\hat{}\ (-U * A_I / M_F * C_{Pf})) + T_S$

T_E = Exit temperature of fluid (°C),

T_I = Inlet fluid temperature (°C),

TS = Final surface temperature of receiver (°C),

U = overall heat transfer co-efficient (W/m²-°C),

A_I = Inner surface area of tube,

M_F = Mass flow rate (grams/ second)

C_{Pf} = Specific heat of fluid (joule/gram- °C).

Overall heat transfer co-efficient (U) is a measure of overall ability of a series of conductive and convective barriers to transfer heat. Here in this case heat is transferred from outside surface to inside surface of the tube which is conduction and the convection is being held through fluid flow and also heat is lost to the surroundings of the tube. [23]

$U = (1 / ((A_A/H_S * A_S) + (1/H_A) + ((A_A * \text{Ln}\ (R_2/R_1)) / (2*Pi*K*N))))$

Where, A_A = Outside surface area of tube (m²),

H_S= Inside heat transfer coefficient (W/m²-°C),

A_S= Inner surface area of tube (m²),

H_A= Outside heat transfer coefficient (W/m²-°C),

R_2= Outer radius of the tube (m),

R_1= Inner radius of the tube (m),

K= Thermal conductivity of material (W/m-°C),

L= Length of the tube.

IV. RESULTS AND DISCUSSIONS

The calculated results are discussed below when the receiver with different dimensions, when two different materials SS316 and Silicon Carbide are used and also when two different fluids are passed such as water and therminal VP1 respectively.

The respective masses of the tubes when SS316 and Silicon Carbide are used, with different dimensions are tabulated below.

TABLE 2.1
MASS OF THE TUBES SS316

Ø mm	**73**	**36**	**23**	**18**	**14**	**12**
Tubes	1	2	3	4	5	6
Thick mm	3	1	1	1	1	1
Mass grams	21085	7028	6627	6828	6526	662 7

TABLE 2.2
MASS OF THE TUBES SILICON CARBIDE

Ø mm	**73**	**36**	**23**	**18**	**14**	**12**
Tubes	1	2	3	4	5	6
Thick mm	3	1	1	1	1	1
Mass grams	8471	2824	2662	2743	2622	2662

Since the density of the silicon carbide is lesser than SS316 obviously whatever the dimensions of the receiver, the mass of SS316 is more. Which results in lesser temperature rise in the material as the mass of the SS316 is more than the silicon carbide and also because of the specific heat of silicon carbide is more than the SS316.

Exit temperatures of the heat transfer fluid when water is used as fluid and when the receiver materials are SS316 and Silicon carbide. The respective surface temperatures attained by materials are same in all the cases calculated.

TABLE 3.1
MATERIAL-SS316, FLUID-WATER

Ø mm/ mass flow rate	**73**	**36**	**23**	**18**	**14**	**12**
3 kg/min	57	114	113	111	110	109
4 kg/min	51	93	92	91	90	89
5 kg/min	46	80	79	79	78	77
6 kg/min	44	73	72	71	71	70

TABLE 3.2
MATERIAL-SILICON CARBIDE, FLUID-WATER

Ø mm / mass flow rate	**73**	**36**	**23**	**18**	**14**	**12**
3 kg/min	76	169	167	165	163	161
4 kg/min	64	135	133	132	130	128
5 kg/min	57	113	112	111	109	108
6 kg/min	53	101	100	99	98	97

The exit temperatures with respective to mass flow rates of the fluid are shown above. In both the cases it can be noted that the exit temperatures are more in case of other than 73 mm outer diameter of the receiver tube. This is because, the 73 mm diameter is a single tube and the other diameter tubes are multiple tubes, each connected at their ends which leads to one inlet and one outlet. The receiver diameters 36 mm, 23 mm, 18 mm, 14 mm and 12 mm are multiple tubes with 2,3,4,5 and 6 respectively. The difference in variation of temperatures in both cases is the fluid gets more time travel from inlet to outlet which helps in more heat transfer.

Exit temperatures of the heat transfer fluid when Therminal VP1 is used as fluid and when the receiver materials are SS316 and Silicon carbide. The respective surface temperatures attained by materials are same in all the cases calculated.

TABLE 4.1
MATERIAL-SS316, FLUID-THERMINAL VP1

Ø mm/ mass flow rate	**73**	**36**	**23**	**18**	**14**	**12**
3 kg/min	97	234	233	229	227	224
4 kg/min	81	187	185	182	180	178
5 kg/min	71	155	154	152	150	148
6 kg/min	65	138	136	135	133	131

TABLE 4.2
MATERIAL-SILICON CARBIDE, FLUID-THERMINAL VP1

Ø mm/ mass flow rate	**73**	**36**	**23**	**18**	**14**	**12**
3 kg/min	142	370	366	361	357	352
4 kg/min	116	290	287	283	280	276
5 kg/min	98	238	236	233	230	227
6 kg/min	89	209	206	204	201	198

From the above results it can be proved that as mentioned earlier it is better to use two or more tubes which are connected to each other than a single tube as a receiver. And also from the results here it can be observed that the therminal VP1 exit temperatures are more when compared with the water as heat transfer fluid.

V. CONCLUSIONS

The results show that, the receiver tube with specifications, receiver material as silicon carbide and heat transfer fluid as therminal VP1 gives better exit temperatures than the other combinations mentioned above. The second better option is SS316 material and therminal VP1 as heat transfer fluid. But this is due to the heat transfer fluid therminal VP1, higher exit temperatures are attained. In case of therminal VP1, a heat exchanger should have to be used for heat exchanging process. Since these are the results which are attained by using minimum assumptions where required. And so the results are considered instantly which will be different when performed experimentally. There will also be change in the final results when performed experimentally because of the heat losses due to different factors like convection and end losses to the support structure. But the comparison ratios of different specifications will be same, so the above suggested specification can be considered as better than the rest. And also the receiver with two or more tubes connected to each other is a better option than a single receiver tube.

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REFERENCES

[1]. Rafael Almanza, Alvaro Lentz and Gustavo Jimenez, 1997 “Receiver behaviour in direct steam generation with parabolic troughs”, Solar Energy Volume 61, No. 4, pages 275–278.
[2]. Hank Price, Eckhard Lupfert, David Kearney, Eduardo Zarza, Gilbert Cohen Randy Gee, Rod Mahoney, May 2002 “Advances in Parabolic Trough Solar Power Technology”, Journal of Solar Energy Engineering, volume 124, pages 109-125.
[3]. Michael John Brooks, February 2005 “Performance of a parabolic trough solar collector”.
[4]. Amirtham Valan Arasu and Samuel Thambu Sornakumar, 2006 “Performance characteristics of the solar parabolic trough collector with hot water generation system”, Thermal science: Volume 10, No. 2, pages 167-174.
[5]. Gang Xiao, October 2007 “A closed parabolic trough solar collector”.
[6]. A. Valan Arasu, T. Sornakumar, 2007 “Design, manufacture and testing of fiber glass reinforced parabola trough for parabolic trough solar collectors”, Solar Energy 81, pages 1273–1279.
[7]. M. Petrakis, G. Barakos and S. Kaplanis, 2009 “Roof Integrated Mini-Parabolic Solar Collectors. Comparison between Simulation and Experimental Results”, The Open Fuels & Energy Science Journal, volume 2, page 71-81.
[8]. Najla El Gharbi, Halima Derbal, Sofiane Bouaichaoui, Noureddine Said, 2011 “A comparative study between parabolic trough collector and linear Fresnel reflector technologies”, Energy Procedia 6, pages 565–572.
[9]. David Barlev, Ruxandra Vidu, Pieter Stroeve, May 2011, “Innovation in concentrated solar power”, Solar Energy Materials & Solar Cells 95, pages 2703–2725.
[10]. Tadahmun Ahmed Yassen, April 2012 “Experimental and Theoretical Study of a Parabolic Trough Solar Collector”, Anbar Journal for Engineering Sciences.
[11]. K. Senthil Manikandan, G. Kumaresan, R. Velraj and S. Iniyan, 2012 “Parametric study of solar parabolic trough collector system”, Asian journal of applied sciences 5(6): 384-393.
[12]. Mohit Bhargva, July 2012 “Modeling, Analysis, Evaluation, Selection and Experimental investigation of parabolic trough solar collector system”.
[13]. Liang Zhang, Wujun Wang, Zitao Yu, Liwu Fan, Yacai Hu, YuNi, Jianren Fan, Kefa Cen, 2012 “An experimental investigation of a natural circulation heat pipe system applied to a parabolic trough solar collector steam generation system”, Solar Energy 86, pages 911–919.
[14]. Soteris A. Kalogirou, 2012 “A detailed thermal model of a parabolic trough collector receiver”, Energy volume 48, pages 298-306.
[15]. Soteris A. Kalogirou, Gregoris Panayiotou, “Evaluation of a parabolic trough collector performance”.
[16]. Saeed Zarrini, Mahmood Yaghoubi and Reza Hessami, “Analysis of incident irradiation on the receiver tube of a parabolic collector in shut down mode”.
[17]. William B. Stine and Michael Geyer, “Power from the Sun”, http://www.powerfromthesun.net.

[18]. Renewables 2012 Global status report, Renewable Energy policy network for 21st century, WWW.ren21.net.
[19]. http://en.wikipedia.org/wiki/Solar_energy.
[20]. http://en.wikipedia.org/wiki/Parabolic_trough.
[21]. http://wims.unice.fr/xiao/solar/efficiency.html
[22].http://www.daerospace.com/HydraulicSystems/PipeFlowEq.php
[23]. http://nptel.iitm.ac.in/courses/Webcourse-contents.
[24]. http://www.sunwindenergy.com.
[25]. http://www.therminol.com/pages/products/vp-1.asp.

A. Pradeep Reddy, I received the Bachelor degree (With First Class) in mechanical engineering from Narasaraopeta Engineering College in Narasaraopeta, Andhra Pradesh, India. I am currently Pursuing M.TECH in energy and environment engineering at the Vellore institute of technology, Vellore and now I am doing M.TECH final year project at B.H.E.L, R&D Division CTI-Bengaluru. My research Topic at B.H.E.L is Design and Development of receiver for utilization of concentrated solar power. My area of interest is Renewable Energy Technology. I am one of the author of the publication in International journal of Science, Engineering and Technology Research with title name Design and Fabrication of Portable Solar fryer and its comparative analysis with SK-14 which is published on Volume 2, Issue 2, February 2013.