Design Optimization and Performance Analysis of Solar Parabolic Trough Collector

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Abstract:

The primary objective of this study is to develop and evaluate low-cost PTC capable of producing warm water for low-temperature applications. A new parabolic trough collector is designed; which is easy to accumulate and transport. Specific facility to accommodate different receiver pipes, various reflector sheets, and different heat transfer fluids. This design also allows for changing the trough's geometrical dimensions. The design has provisions to attach an automatic tracking system and glass cover.

In this study, a prototype of solar parabolic trough collector (PTC) is investigated to study experimental, optical, and thermal efficiencies. Three different reflectors and three different receiver pipes with and without black graphite paint coating are tested. This study deals with some of the feasible solutions to find out theoretical efficiency, optical efficiency, and intercept factor. The design of experiment technique is used to design and analyze experiments. A regression model is prepared based on the analysis. As a solution, a combination of intercept factor=0.231 and receiver value = 0.98 is found to be the best-fitted pair. Maximum efficiency of η_{theo} = 15.28%, η_{opt}=15.99%and η_{exp} =12.38% is obtained.

This Novel PTC has further experimented with three different attachments Manual tracking with and without glass cover and Automatic tracking. Experimental, Optical, and Theoretical efficiencies were calculated for all three PTC systems. Average experimental efficiencies of PTC with Manual tracking, Manual tracking with a Glass cover, and Automatic tracking are 11.8%, 13.5%, and 14.9 % respectively. Brief economic analysis is also carried out for all three PTC systems. Cost of water heating per kg for manual tracking PTC system is only 0.3/- INR and for Manual tracking with a Glass cover and Automatic tracking it is equivalent to 0.4/- INR. The payback period for all is equivalent to 4 years for a PTC system for manual tracking and for PTC systems of Manual tracking with a Glass cover and Automatic tracking it is found equivalent to 5 years. Experimentation conducted at the specific location in Godhra, Gujarat, India latitude of 22.7788°N and longitude of 73.6143°E.

Introduction

History of solar parabolic trough collector (PTC) is more than 130 years old, In an era of 1880, PTC was first brought in by John Ericsson, who used it to power a steam engine [1]. This idea was used by Shumand and Boys for an irrigation purpose in the Nile river area in 1912 [2]. PTC attracts researchers due to its ample applications. Number of researchers started working on various applications of PTC. The most significant application of PTC is electricity generation as it can produce temperature up to 400^0C [3]. PTC has advantages like high power capacity, modularity, high efficiency, versatility long life, and durability against moisture. It has disadvantages too like need of moving parts, deformation of the receiver, the high maintenance cost of the tracking system, and large land area [4][5]. A combination of convention gas-powered power stations and concentrated solar systems like parabolic trough collectors increase the efficiency of the system, reducing the cost of electricity generation, and can be used as backup support [6]. Up to 2010 capacity of global Concentrated Solar Power plants was nearly about 1 GW, which is likely to increase by 7 % and 25 % up to 2030 and 2050 respectively [7]. Reddy et al. (2012) analyzed electric power generation using oil and water as a heat transfer fluid. They carried out a techno-economic feasibility analysis of a solar trough power plant at 58 different locations in India. They concluded that the optimum configuration of the collector field was considered as 6 m with a rim angle of 65°[8].Solar energy has significant applications in favor of mankind and many researchers are working on different aspects of it.

Solar parabolic trough collector is categorized in two parts. First is a full-grown technology mostly used in electricity generation [6]. It has a heating temperature range of up to 400^0C [3]. The second category is having different applications like water distillation, industrial process heat, refrigeration, and air conditioning, air heating, food processing, etc. [9][10][11]. This second category has a low to medium temperature range. Most of the researchers are working on this second category of parabolic trough collectors [7] [8]. PTC is a line focusing, concentrating solar collector. Reflector, receiver or absorber, structure, tracking system, and storage system are physical parts of PTC. Reflectivity, intercept factor, mass flow rate, heat transfer fluid, and applications are the main core areas of PTC in which researchers are working.

Brief description on the state of the art research topic

An in-depth review of various geometrical parameters of PTC and multiple applications is carried out. Key parameters of a PTC are concluded in graphical form in Figure 1. The key parameters affecting the efficiency of PTC are structural and optical performance, thermal performance, thermal storage device, solar tracking mechanisms, and applications. Structure of PTC is the main critical parameter for the design, cost, and performance of PTC. Improved structure can enhance efficiency and reduce operational costs. Heat transfer fluid is the second most essential parameters; Research stated that with the use of molten salt as an HTF, PTC could achieve 520^{0}C temperature. Now a day's nanoparticles are used in HTF to achieve higher efficiency [14].

Water is the most general heat transfer fluid. Reflector is the costliest part of the PTC. Silver coated polymer film, aluminum foil; silver coated PVC sheet and anodized aluminum sheets are used as low-cost alternative reflectors. SOLARFLEX foil is a broadly used alternative of a curved mirror [15]. The receiver should have low heat losses and should absorb high radiation. Glass tube cover, selective coating on receiver tube, pin fin inserts and porous media inside the tube is used to improve the effectiveness of the PTC [16]. PTC is a concentrating solar system, so it requires a minimum of one-axis tracking. North-south alignment with east-west monitoring is preferred in single axis tracking. A thermal storage system is bifurcated in two parts passive and active storage systems. Thermal storage system should place closed to the PTC system to avoid thermal losses. PTC can be used in various applications due to its versatility in design, size, and temperature range. Primary implementation of PTC is the production of electricity as a power plant. Claims noted down apart from electricity generation are water distillation, industrial process heat, solar cooling and refrigeration, air heating, water heating. In an application like air heating, solar cooling, and freezing, industrial process heat PTC is replacing traditional solar collectors. PTC has a potential to replace the conventional flat plate collector for domestic water heating.

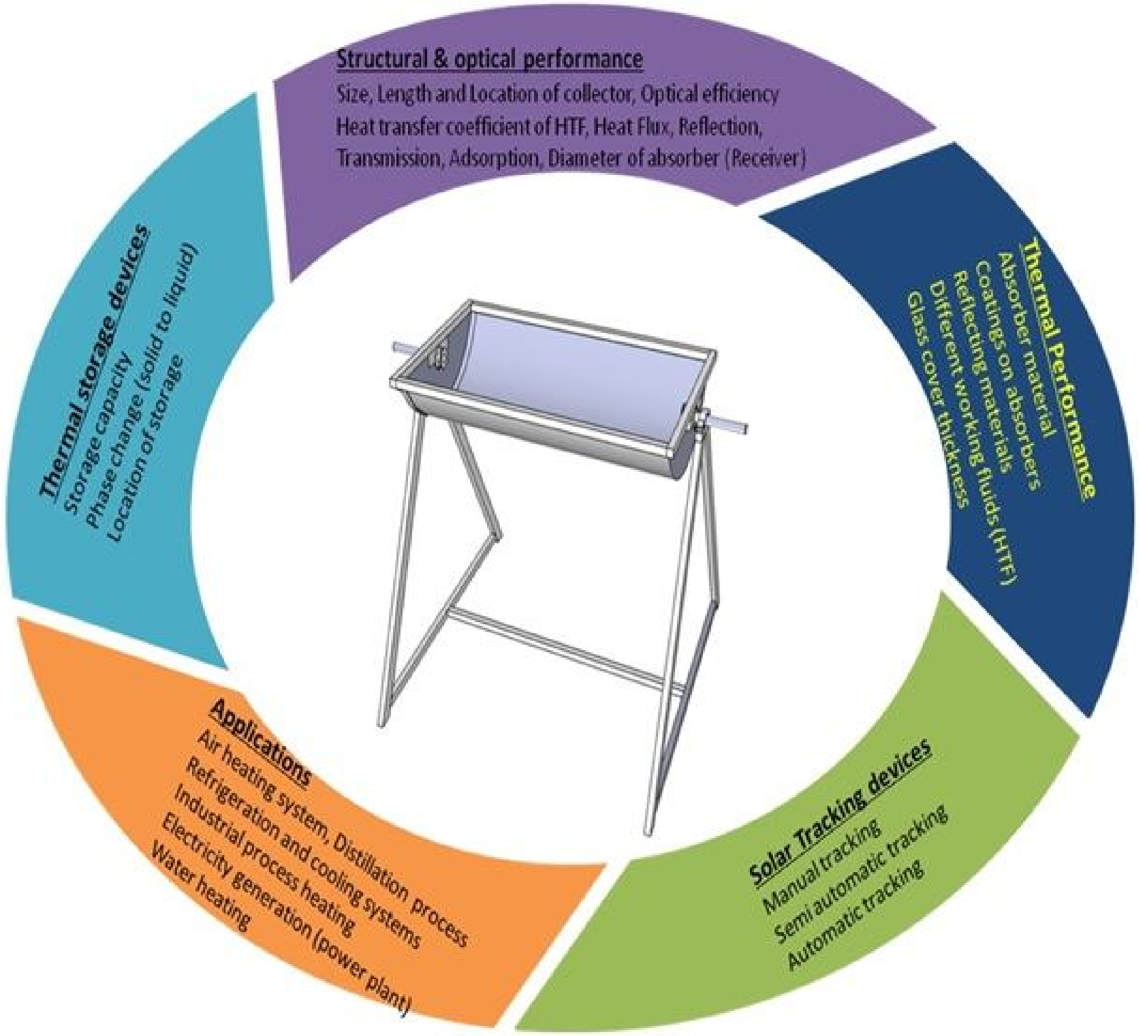

Figure 1 Key parameters of PTC

Definition of the Problem

This is an experimental attempt to "Design Optimisation and Performance Analysis of Solar Parabolic Trough Collector". A novel and flexible design of PTC is developed which can attract researchers to test the suitability of various parameters; i.e. different reflective materials, receiver pipe diameter, and types, various HTF and focal length; for different domestic applications and the region of installation.

In this study, a prototype of solar parabolic trough collector (PTC) is investigated to study experimental, optical, and thermal efficiencies. Three different reflectors and three different receiver pipes with and without black graphite paint coating are tested. This study deals with some of the feasible solutions to find out theoretical efficiency, optical efficiency, and intercept factor. The Design of Experiment (DOE) technique is used to design and analyze experiments. This Novel PTC has further experimented with three different attachments Manual tracking with and without glass cover and Automatic tracking. Experimental, Optical, and Theoretical efficiencies calculated for all three PTC systems.

Objective and Scope of Work

From the literature survey, it is found that PTC can be used in various applications due to its versatility in design, size, and temperature range. The primary implementation of PTC is the production of electricity as a power plant. The claims noted down apart from electricity generation are water distillation, industrial process heat, solar cooling and refrigeration, air heating, water heating. In an application like air heating, solar cooling, and freezing, industrial process heat PTC is replacing traditional solar collectors. PTC has the potential to replace the conventional flat plate collector for domestic water heating.

Objectives:

- The primary objective is to design and develop a PTC suitable for domestic/low-temperature water heating.
- To study the effect of various absorbers with and without coating on performance of PTC.
- To study the effect of various reflective materials on performance of PTC.
- To find theoretical efficiency of proposed system.

Scope of work:

- Design and develop PTC suitable for domestic/low-temperature water heating.
- Leakages occurs in flexible joints due to rotation of receiver.
- Solar tracking system.
- Dust decreases the efficiency of collector.

Original contribution by the thesis

A novel and flexible design of PTC is developed which can attract researchers to test the suitability of various parameters; i.e. different reflective materials, collector pipe diameter, and types, various HTF and focal length; for different domestic applications and the region of installation. The main advantages of the design are as follows.

- The design is easy to manufacture.
- Easy to maintenance. In a conventional domestic solar water heater, the main disadvantage is maintenance and dis-assembling which is too simple in this design.
- Easy to transport.
- Can change the reflector sheet as per season or requirement.
- Easy to change the collector pipe. This can be the great advantage of this design as most of the available designs for domestic water heating systems suffer from the blockage of collector pipes due to scaling inside it, and rigid design limits the changing of the collector pipe.
- High rim angle and rectangular frame structure so we can place a glass sheet to minimize wind effect, dust effect and improve the thermal efficiency of the system.
- Suitable for connecting domestic water line connections.
- The overall weight of the system is 30 kg.
- As a total load of a trough is concentrated on bearing, less force is required for tracking.
- A low-cost Automatic tracking system can be installed.
- Design suitable for employing glass cover on a trough. It can help with dust protection.
- Resolved problem of leakage due to a flexible joint of receiver connections.

In addition, proposed work reflected in following literature.

1. Identification of research problems after the literature survey is reflected in the review paper published in SCOPUS Journal. (DOI:10.1080/01430750.2019.1636869)
2. Design and development of PTC published in UGC approved journal. (DOI:10.22214/ijraset.2017.10073)
3. Comparative study of experimental work is published in SCI journal. (DOI:10.1080/15567036.2020.1779874)
4. Design of novel PTC filled and published in the Indian patent office. A patent published application number 201921023494 Dated 21/06/2019

Methodology of Research, Results / Comparisons

The primary objective of this study is to evaluate newly developed parabolic trough collector. This PTC is capable of heating water for domestic needs. Three different reflector sheets and three different receivers are experimented in January to March (2019-2020) at the specific location of Godhra, Gujarat, India. All receivers are experimented as non-coated and coated with black graphite paint. The Parabolic trough collector has been designed and developed by considering input factors; inlet water temperature, outlet water temperature, water flow rate, temperature of receiver pipe, reflectivity of a reflector, and emissivity of coated and non-coated receiver tube as controllable factors. Solar radiations, wind speed, and ambient temperature are uncontrollable factors. Instantaneous, optical, and thermal efficiencies are calculated using the above-measured factors as output. The design of experiments method is adopted. A multi-level, multi-factor full factorial design methodology is applied. Regression analysis is performed using Minitab software. The field experiments for the current work were conducted at Government Engineering College, Godhra at latitude of 22.7788°N and longitude of 73.6143°E.

The schematic of the experimental setup is shown in Figure 2 and the actual setup shown in Figure 3.

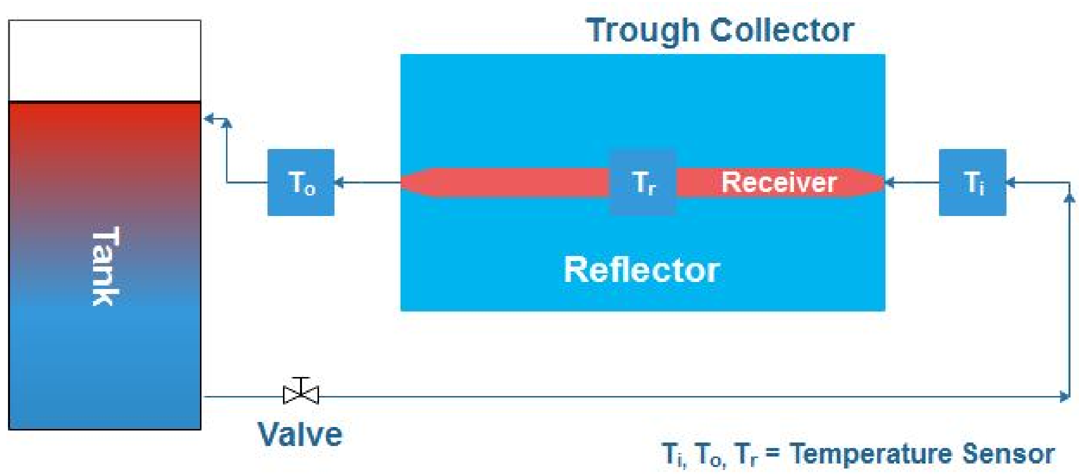

Figure 2 Schematic of the Experimental Setup

Figure 3 Photos of Actual Setup

In this study experimental learning of PTC is carried out with three different reflectors paired with six different receivers. The design has provisions to attach an automatic tracking system and glass cover. This Novel PTC is further experimented with three different attachments Manual tracking, with and without glass cover, and automatic tracking. Brief economic analysis is carried out for all three PTC systems. The final geometrical properties of novel PTC are shown in Table 1 and the optical properties of reflectors are shown in Table 2. Receiver properties are shown in Table 3. Receivers are coated with black graphite paint.

Table 1 Geometrical Properties of PTC

Description	Values
Collector length	1.1 m
Collector Width	0.60 m
Concentration ratio	11.66≈12
Focal distance	0.156 m
Receiver inner diameter	0.018 m
Receiver outer diameter	0.02 m
Receiver Length	0.90 m
Rim angle	98^0
Storage tank capacity	30 ltr.
Receiver material	Copper, Aluminum, G.I.

Table 2 Optical Properties of Reflectors

Reflector	ρ_m = Reflection coefficient (%)	γ = Intercept factor
Acrylic Mirror	81.64	0.186
Chrome Sticker	70.60	0.231
Aluminum Foil Tape	69.41	0.172

Table 3 Receiver Properties

Receiver	ε	α
Copper Non-coated	0.03	0.30
Copper Coated	0.56	0.98
Aluminum Non-coated	0.03	0.16
Aluminum Coated	0.63	0.96
G.I. Non-coated	0.175	0.44
G.I. Coated	0.56	0.85

Full factorial multi-functional multi-level DOE is prepared in Minitab software and Eighteen runs are carried out. For better results and analysis one replication is conducted so 36 runs were performed as per the design table generated. A 95 % confidence level is taken for analysis. Results of these experiments are shown in the form of graphs and tables. Regression analysis has been carried out for mathematical representation of η_{theo}, η_{opt}, and η_{exp}. It is useful for further prediction of the system. It is shown in Table 4.

Table 4 Regression Model

Sr	Type	Regression Model	R-sq	R-sq (adj)	R-sq (pred)
1	η_{theo}	η_{theo} = 0.96 - 5.84 Intercept Factor + 2.13 Receiver + 61.5 Intercept Factor*Receiver	98.14%	97.97%	97.76%
2	η_{exp}	η_{exp} = -0.40 + 8.8 Intercept Factor + 2.35 Receiver + 31.5 Intercept Factor*Receiver	87.8%	86.66%	84.84%
3	η_{opt}	η_{opt} = 2.87 Receiver + 59.5 Intercept Factor*Receiver	98.29%	98.13%	97.97%

From the main effect plot Figure 4 and Figure 5, it has observed that increasing the level of intercept factor and receiver coating efficiency also increase. Receiver coating is affecting more than the intercept factor. By increasing the level of both factors efficiency also increases it shows that both the factors are significant factors hence experimental process is validated.

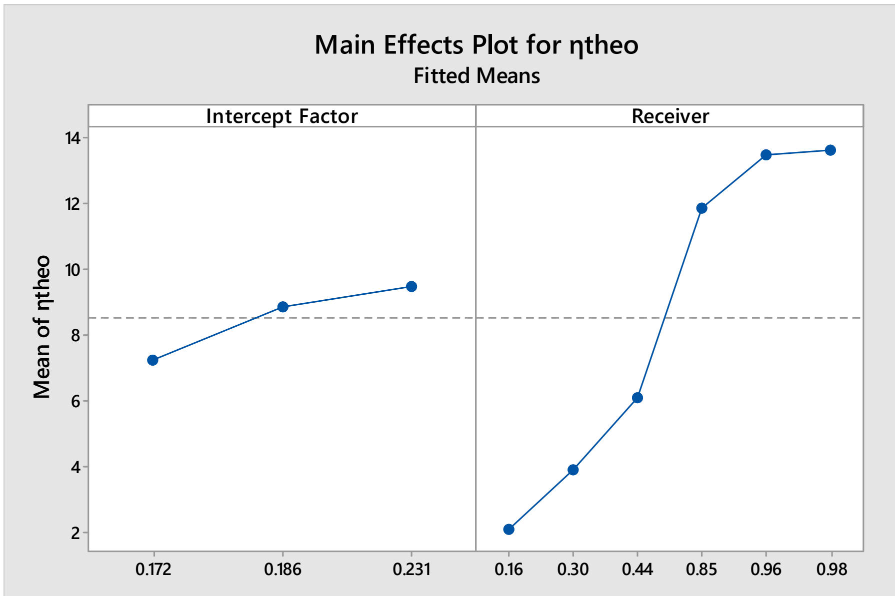

Figure 4 Main Effect Plot for η_{theo}

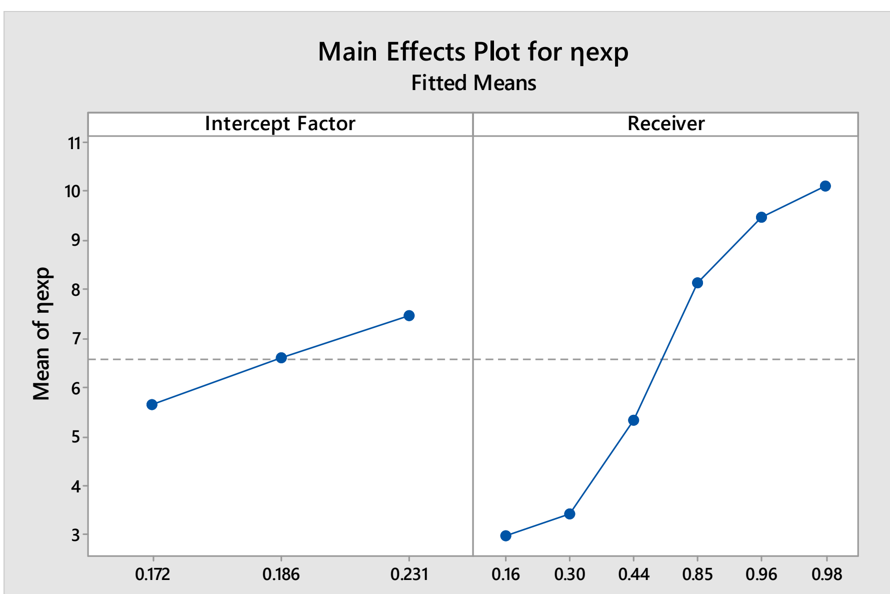

Figure 5 Main Effect Plot for η_{exp}

Response optimization is carried out with the given data. A maximum is the better condition is chosen as we required higher efficiency. As a solution; combination of intercept factor=0.231(Chrome reflector) and receiver value = 0.98 (Copper coated) is the best-fitted pair as shown in Table 5. Chrome reflector with copper black coated receiver is giving maximum efficiency of η_{theo}=15.28% and η_{exp} =12.38%.The obtained efficiencies are in good agreement with Bharti et al.(2019) and D. Kumar et al.(2018) [17][18].

Table 5 Response Optimization: η_{theo}, η_{exp} (Solution)

Response Optimization: η_{theo}, η_{exp} (Solution)					
	Intercept Factor	**Receiver**	**η_{theo} Fit**	**η_{exp} Fit**	**Composite Desirability**
Solution	0.231	0.98	15.28	12.38	0.984417

All three experimental, optical, and theoretical efficiencies are calculated using listed equations. Most of the researchers reported any one or two efficiencies in research papers. It is very difficult to find optical efficiency experimentally. Most of the reported optical efficiency is calculated using numerical techniques so co-relation between experimental and theoretical efficiency is difficult to match. Here efforts are made to calculate all the efficiencies with experimental data and it is found that variation in efficiency values are within a difference of 5 %. Calculated efficiencies using different reflectors and receivers are shown in the form of graphs in Figure 6, Figure 7, and Figure 8.

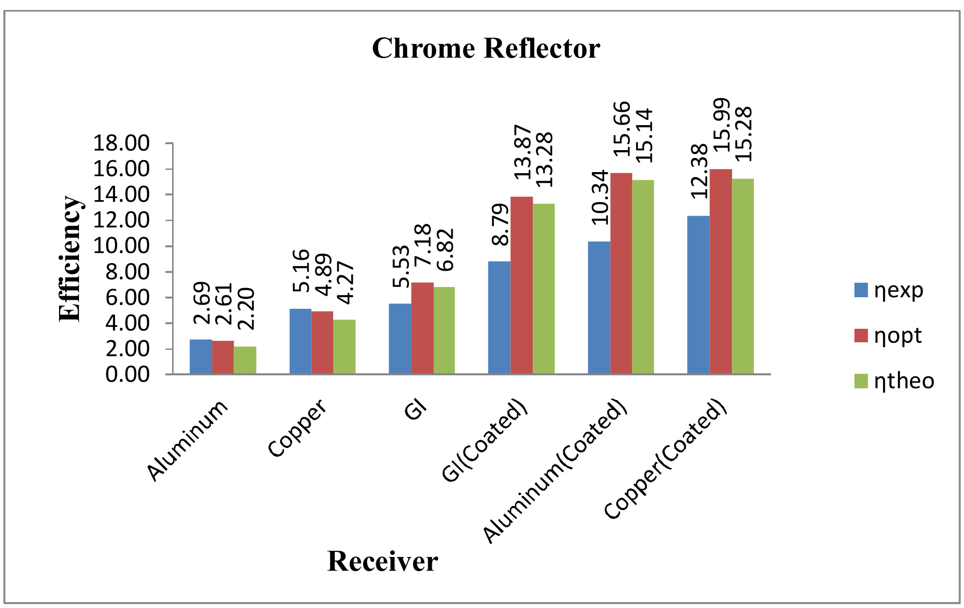

Figure 6 Graph of Average efficiency of Collector with Chrome Reflector

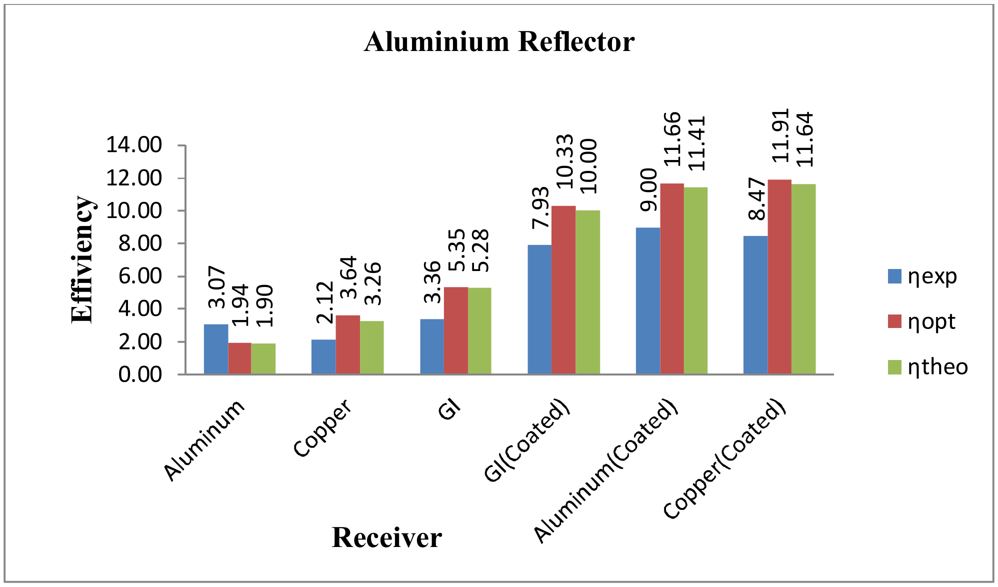

Figure 7 Graph of Average efficiency of Collector with Aluminum Reflector

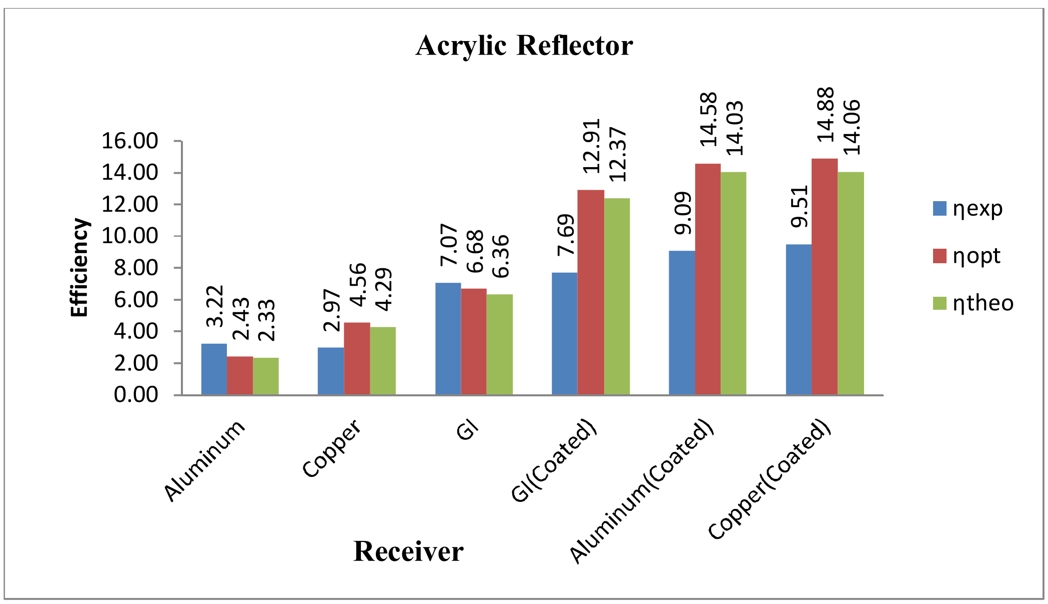

Figure 8 Graph of Average efficiency of Collector with Acrylic Reflector

Novel PTC is having features like attachments of the automatic tracking system and glass cover. So it is planned to test all features of novel PTC. Three setups are developed for all three arrangements. For efficient results all tests are repeated. PTC with Chrome reflector and copper coated receiver is used for experimentations. Results of the six tests are shown in Table 6. The average experimental efficiency of PTC with manual tracking, manual tracking with a glass cover, and automatic tracking is 11.83%, 13.50%, and 14.94 % respectively. No significant difference recorded in theoretical efficiency.

Table 6 Results of Experimentation with Attachments

Sr. No.	Date	Tracking	η_{exp}	η_{opt}	η_{theo}
1	12/3/2020	Manual	11.42	15.99	15.65
2	13/3/2020	Manual	12.23	15.99	15.82
3	12/3/2020	Automatic	15.77	15.99	15.37
4	13/3/2020	Automatic	14.11	15.99	15.91
5	12/3/2020	Glass cover manual	13.55	15.99	14.44
6	13/3/2020	Glass cover manual	13.44	15.99	15.70

The annual cost of water heating per kg for all three systems is calculated [19].Generally it is calculated per meter square. The proposed novel PTC has an area of 0.66 m^2 so, it is reported by considering that factor. It is shown in Table 7.

Table 7 Annual cost of water heating per kg

Cost (INR)	Manual Tracking	Automatic Tracking	Manual Tracking with a Glass cover
Capital cost (P)	5330	6580	7090
Salvage Value (S) (10% of principal value)	533	658	709
Life of System (n) years	20	20	20
Interest rate (i) %	0.10	0.10	0.10
Capital Recovery Factor (CRF)	0.1	0.1	0.1
Sinking Fund Factor (SRF)	0.0	0.0	0.0
Annual First Cost = (CRF*P)	565.4	698.0	752.1
Annual Salvage Value (SFF*P)	32.4	40.0	43.1
Annual Maintenance Cost (Rs. 0.15* Annual First Cost)	84.8	104.7	112.8
Annual First Cost /m^2= (Annual First Cost + Annual Maintenance Cost-Annual Salvage Value) x 0.66	407.8	503.4	542.4
Annual cost of water heating (ACWH)	1338.1	1364.2	1504.8
Annual cost of water heating per kg = Annual First Cost/annual cost of water heating (ACWH)	**0.3**	**0.4**	**0.4**

The payback period is used frequently for judging the economic viability of a solar system. It is defined as a time taken for cumulative saving on energy or income to become equal to the initial investment[19][20][21]. The operating cost of the proposed system is zero. It is shown in Table 8.

Table 8 Payback Periods

Cost (INR)	Manual Tracking	Automatic Tracking	Manual Tracking with a Glass cover
Capital cost (P)	5330	6580	7090
Operating cost	0	0	0
Annual Maintenance Cost (Rs. 0.15* Annual First Cost)	84.8	104.6	112.8
Annual cost of water heating (ACWH)	1338.0	1364.2	1504.8
Subsidized cost given by government sectors is taken as 4% (Capital cost * 0.04)	213.2	263.2	283.6
Net Profit = Annual cost of water heating (ACWH) - operating cost-Maintenance cost	1253.3	1259.5	1392.0
Payback period (Years) = (Investment - Subsidized cost) /(Net Profit)	**4.1**	**5.0**	**4.9**
Payback period (Without Subsidy) (Years) = (Investment) /(Net Profit)	**4.3**	**5.2**	**5.1**

Solar savings can be earned by selling carbon credits. This earning can be used to reduce the payback period. Carbon credits earned by all three systems are shown in the following Table 9. Solar saving by carbon credit earned is nearly the same as capital cost after 20 years as the lifespan of the proposed novel PTC system is estimated to 20 years.

Table 9 Carbon Credit Earned

Data	Manual Tracking	Automatic Tracking	Manual Tracking with a Glass cover
CO_2 Reduction /Annum (tCO_2e)	0.189	0.193	0.213
Carbon Credit Earned/Annum (INR)	329.4	335.8	370.4

Achievements with respect to objectives

Objectives	Achievements
▸ To design and develop PTC suitable for domestic/low-temperature water heating	Designed and developed PTC suitable for low-temperature water heating. Design is registered for patent filing. A Design patent is published. Project selected for patent filing and funded by GTU SSIP IPR support. (18/04/2019)
▸ To study the effect of various absorber with and without coating on performance of PTC.	Studied the effect of three heat collector. Copper, Aluminum, and G.I. receivers with and without coating are investigated. Effect of black graphite coating on all three heat collector studied. Pair of chrome sticker with black coated copper receiver give maximum efficiency of η_{exp}=12.38 %, η_{opt} = 15.99 %, and η_{theo}=15.28%.
▸ To study the effect of various reflective material on performance of PTC.	Studied the effect of three reflective materials. Acrylic mirror, Aluminum foil tape, chrome sticker are investigated, and Intercept factors found as 0.186, 0.172, 0.231 respectively.
▸ To find theoretical efficiency of proposed system.	A theoretical investigation carried out and all three efficiencies of all pairs are calculated. DOE and regression analysis carried out. It is found that all factors are effecting the experimentation.

In addition to above achievements experimentation performed on various attachments and the average experimental efficiency of PTC with manual tracking, manual tracking with a glass cover, and automatic tracking is 11.83%, 13.50%, and 14.94 % respectively. Economic analysis is also executed and the payback period is found equivalent to 4 years for a PTC system for manual tracking and for PTC systems of manual tracking with a glass cover and automatic tracking it is found equivalent to 5 years.

Conclusion

This study evaluates newly designed PTC with three reflectors and six receivers. Further it is also evaluated by attaching three attachments. With results, it is proven that developed novel PTC is capable of producing low-temperature water heating. Due to novel arrangements, no flexible joint required for receiver joints and no water leakage problems accrued. Following points are concluded from present work,

- A receiver and intercept factor both are significant factors, but a receiver is the most dominant factor in experimentation on PTC. In DOE analysis receiver's percentage contribution is higher than the intercept factor.
- It is found that the Intercept factor is a significant factor. It largely affects the performance of PTC: the higher the intercept factor higher the efficiency.
- Further using these values optical and theoretical efficiencies are calculated which are found in the range comparison with experimental efficiencies.
- The highest value of the intercept factor is 0.231 for the chrome reflector setup. This is because of the manufacturing process errors and non-parabolic shape. If it is rectified, then this system can give higher efficiency.
- Chrome sticker reflector works efficiently for a long time. Dust deposing and moisture does not affect the efficiency of it.
- Aluminum and other metallic reflectors failed to serve for a long time. cavitation form on the surface of the reflector due to moisture contents and dust particles create screech marks on the reflector surface which decreases optical efficiency.
- Black graphite paint coating on a receiver increase the thermal efficiency of the system.
- For domestic water heating, this much efficiency is good enough. This represents the acceptability of PTC made with moderate technology for the domestic water heating systems.
- Response optimization method is carried out using the maximum is a better condition. As a solution combination of intercept factor=0.231 (Chrome Reflector) and receiver value = 0.98 (Copper Coated) is the best-fitted pair.
- All three experimental, optical, and theoretical efficiencies are calculated. It is found that variation in efficiencies values are within a difference of 5 %.
- This study evaluates newly designed PTC with three attachments. With results, it is proven that developed novel PTC is capable of producing low-temperature water heating. Due to novel arrangements, no flexible joint required for receiver joints and no water leakage problems accrued.

- The automatic tracking PTC system works excellent with the highest experimental efficiency of 15.77 %, which is closest to theoretical efficiency.
- Wind speed affects the efficiency of manual and automatic systems, but it is stable in manual tracking with the glass cover PTC system.
- The annual cost of water heating (ACWH) for the PTC with Manual tracking, Manual tracking with a Glass cover, and Automatic tracking is 1338/-, 1509/- and 1364/- INR respectively.
- The cost of heating 1 kg of water is less than 0.50 paisa (INR). For manual tracking, the PTC system is only 0.3/- INR, and for Manual tracking with a Glass cover and Automatic tracking, it is equivalent to 0.4/- INR.
- Payback time for manual tracking PTC is 4.1 years considering subsidy when it is 4.3 years without considering subsidy. For PTC systems of Manual tracking with a Glass cover and Automatic tracking, it is found 5.2 years and 5.1 years without subsidy respectively.
- CO_2 Reduction per annum (tCO_2e) for the PTC with Manual tracking, Manual tracking with a Glass cover, and Automatic tracking is 0.189, 0.193, and 0.213 respectively.

PUBLICATIONS

1. B.H. Upadhyay, A.J. Patel, P. V. Ramana, A detailed review on solar parabolic trough collector, Int. J. Ambient Energy. 0 (2019) 1–21. DOI:10.1080/01430750.2019.1636869.

2. B. H. Upadhyay, A. J. Patel, and P. V Ramana, "Parabolic Trough Collector, a Novel Design for Domestic Water Heating Application," *IJRASET*, vol. 5, no. X, pp. 497–503, 2017.DOI: 10.22214/ijraset.2017.10073

3. B.H. Upadhyay, A.J. Patel, P. V Ramana,"Comparative study of parabolic trough collector for low-temperature water heating," Energy Sources, Part A Recover. Util. Environ. Eff. 0 (2020) 1–17. DOI:10.1080/15567036.2020.1779874

PATENT

Upadhyay Bhargav H, Dr. Patel Amitkumar J. Dr. P.V.Ramana, PARABOLIC TROUGH TYPE SOLAR ENERGY COLLECTOR FOR DOMESTIC WATER HEATING, Indian Patent,201921023494, Published 21/06/2019

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