Case Studies in Thermal Engineering 14 (2019) 100436

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

An investigation of a solar cooker with parabolic trough concentrator

Muhammad Noman[a], Ahmad Wasim[a], Muzaffar Ali[b], Mirza Jahanzaib[a], Salman Hussain[a], Hafiz Muhammad Khurram Ali[a], Hafiz Muhammad Ali[b,*]

[a] *Industrial Engineering Department, University of Engineering and Technology, Taxila, Pakistan*
[b] *Mechanical Engineering Department, University of Engineering and Technology, Taxila, Pakistan*

ARTICLE INFO

Keywords:
Energy and exergy efficiency analysis
Mathematical model
Performance evaluation
Solar parabolic trough cooker

ABSTRACT

This research aims to develop a simple mathematical model for performance evaluation of a thermally exposed solar parabolic trough cooker. It was done under open environmental climate conditions for domestic uses. The experimental setup consisted of a solar cooker made of polished parabolic trough stainless steel having concentration ratio 9.867. The efficiency analysis depicts that the resulted parabolic trough optical efficiency range between 53-33%, theoretical efficiency between 50-30% and the experimental efficiency between 38-5%. Additionally, the maximum water temperature achieved was 37.2 °C at the outlet of parabolic trough. However, maximum water temperature achieved by parabolic trough cooker was 53.6 °C under stagnated conditions. Furthermore, the observed cooker energy efficiency range between 6.5-0.11% and exergy efficiency was in range between 7.6×10^{-2} - 2.1×10^{-2}% for direct cooking. Results found helpful for making domestic useable cooker.

1. Introduction

Wood, biomass and fossil fuels are being used as cooking fuels worldwide on large scale. These elements not only cause environmental hazards but also lead to rapid deforestation, global warming, and depletion of natural resources [1]. To resolve these issues, environmental agencies are working hard in searching climate friendly solutions. Even the top energy consumption countries proposed to utilize renewable energy sources instead of fossil fuels [2]. A study of National Renewable Energy Laboratory (NREL) in collaboration with USAID reveal that Pakistan has solar energy potential of 2.9 Million MW [1]. Pakistan is an emerging country, with population of more than 180 million, facing sever energy crises [3–5]. Statistics reflects that energy import bill of Pakistan for domestic sector is 41% of total bill [6]. To overcome above mentioned problem and energy crises of Pakistan, cooking through renewable energy resources such as solar energy, solar cooking, found as a potential solution. (see Table 1)

Solar cookers (SC) comes under different categories that depend on technology deployed for it. These technologies includes concentrating and non-concentrating technologies [7–9]. Concentrating technologies include parabolic trough concentrator (PTC), parabolic dish, linear Fresnel reflector (IFR) and central receiver tower [10]. Among these, PTC has found better and feasible solution due to rapid achievement of high temperatures of 60°C–400 °C [7,9,11]. In Pakistan many studies proposed PTC for solving energy

* Corresponding author.
E-mail addresses: muhammad.noman@uettaxila.edu.pk (M. Noman), wasim.ahmad@uettaxila.edu.pk (A. Wasim), muzaffarali79@yahoo.com (M. Ali), jahan.zaib@uettaxila.edu.pk (M. Jahanzaib), salman.hussain@uettaxila.edu.pk (S. Hussain), khurram.ali@uettaxila.edu.pk (H.M.K. Ali), h.m.ali@uettaxila.edu.pk (H.M. Ali).

https://doi.org/10.1016/j.csite.2019.100436
Received 24 February 2019; Received in revised form 21 March 2019; Accepted 25 March 2019
Available online 26 March 2019

Table 1
Parameters used in mathematical model [24].

Symbol	Design Value	Symbol	Design Value	Symbol	Design Value	Symbol	Design Value
A_{ap}	1.033	α_r	0.85	d_{re}	0.019	ϱ_r	1.50E^{-06}
A_{re}	0.104	$\in_r$	0.78	d_{ri}	0.011	γ	0.9
A_{ri}	0.060	σ	5.67E-08	f	0.140	$\dot{M}$	0.23
A_f	0.1	λ_r	401	Lr	1.75	T_{ss}	6000
C	9.867	ρ_o	0.75	M	20	$\dot{m}$	0.032
W	0.609	ϑ_o	57				

crises [12]. PTC based solar cooker (PTSC) consists of PTC with a cooking pot located on the focus point or line of PTC [13].

Among the various studies of solar cookers and PTC, some have focused on local applications and one type of cooker, while, various on thermal storage unit and on structure of cooker [14]. Moreover, others proposed phase mixtures and Nano fluid for thermal enhancement of PTC [15,16]. Recently, studies have been conducted on economic aspects of solar cooking system in specific region such as Lebanon [9] and India [17]. Also, many studies analyzed and compared various types of solar cookers conducting energy and exergy analysis for evaluating their thermal performances [18–22].

It can be observed from the literature that many studies are focused on the end applications in which detailed energy and exegetic analysis at the design stage is rarely performed under a specific local climate condition. Therefore, in this study a detailed experimental performance analysis of PTC is evaluated in terms of energy and exergy analysis under wide range of real winter climate conditions. In addition, the experimental setup is fabricated with locally available PTC materials in terms of reflector and absorber which is a step forward for the indigenous solution. So that, a real applied performance evaluation could be recognized in Taxila, Pakistan. It's done by i) determining performance evaluation of PTC ii) exergy and energy efficiency analysis for direct cooking of PTC. Solar cooking performance evaluated in real time conditions, exposed to environment inclusive all thermal heat losses yielding the sizing of the system and performance efficiency means to be productive.

2. Research methodology

PTSC developed through extensive literature of solar cooking system and dominative industrial renewable thermal technologies. To evaluate PTSC system performance, the system analyzed theoretically and experimentally. For this purpose, following work done.

i Performance evaluated of the parabolic trough
ii Energy and exergy analysis of the solar cooking system for direct cooking

The schematic diagram of parabolic trough system has been described in Fig. 1. The parabolic trough consists of reflecting surface, absorber pipe exposed to environment, heat transfer fluid (HTF). Fig. 1.a showing the schematic diagram of parabolic trough system in which PTC, valves, thermos couples, water tank and a pump is shown.

2.1. Performance evaluation of the parabolic trough

The performance of PTC evaluated by studying and manipulating various existing mathematical model [23–28]. It is mandatory to be aware of optical efficiency, theoretical efficiency and experimental efficiency of developed system to evaluate the performance of the PTC.

The **optical efficiency** can be calculated using relation shown in Eq. (1) [25].

$$\eta_o = \rho_c \alpha_r \gamma [(1 - A_f \tan\theta)\cos\theta] \tag{1}$$

Fig. 1.a showing systematic diagram of PTC system.

Theoretical efficiency is the portion of energy that contributes to increase the temperature of fluid circulating in the system and it is calculated though Eq. (2) [27].

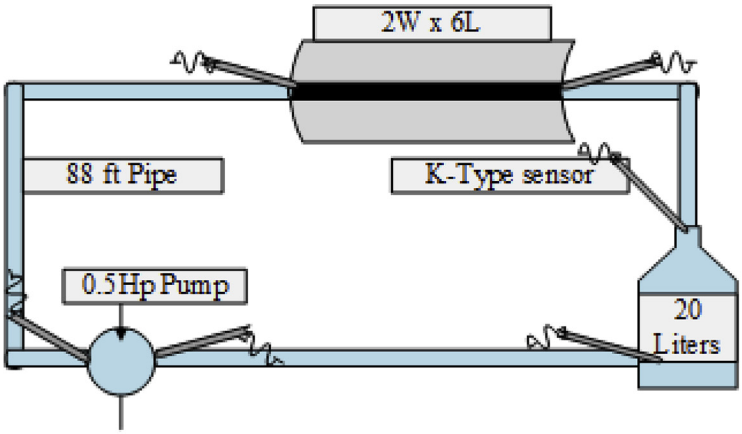
$$\eta = Q_r \left[\eta_o - \frac{Q_l (T_{f,in} - T_a)}{C.\, DI} \right] \tag{2}$$

Experimental efficiency at any instant is determined through Eq. (3) [27].

$$\eta_c = \frac{Q_f}{Q_{rad,ca}} = \frac{\dot{m} C_p (T_{f0} - T_{fi})}{DNI.\, \eta_o.\, A_{ap}} \tag{3}$$

2.2. Direct cooking energy and exergy analysis

PTSC direct cooking energy and exergy mathematical analysis model is developed and its performance analyzed at stagnated



1.1: Schematic diagram of parabolic trough system

1.2: Experimental Setup of Parabolic trough collector

Fig. 1. Parabolic trough system. (1.1): Schematic diagram of parabolic trough system, (1.2): Experimental Setup of Parabolic trough collector.

condition. It has been done by filling the absorber pipe with water and closing it both ends with valves as shown in Fig. 1.a and Fig. 2. PTSC experimented under real conditions through energy and exergy analysis. All experiments were performed in between from 10:30 a.m. to 3:00 p.m.

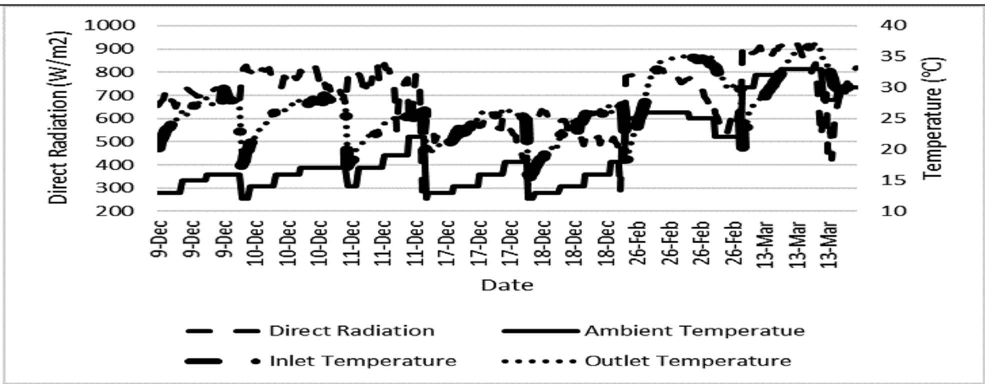
2.2.1. Energy analysis

Energy analysis based on the first law of thermodynamics. This analysis determines the net heat supplied converted to work for cooking. Energy analysis ignores the reduction in potential of energy that limit its effectiveness. In SC case, the energy analysis can only be used for sizing and analyzing a system that is solely based on one type of energy. The E_o energy output by the fluid due to rise in temperature to the energy input due to solar radiation on the cooker. Energy input E_i from the sun in form of solar radiation to the solar cooker determined through Energy Efficiency η_{ENERGY} which is ratio of energy output to energy input determined through Eq. (4) [13,18].

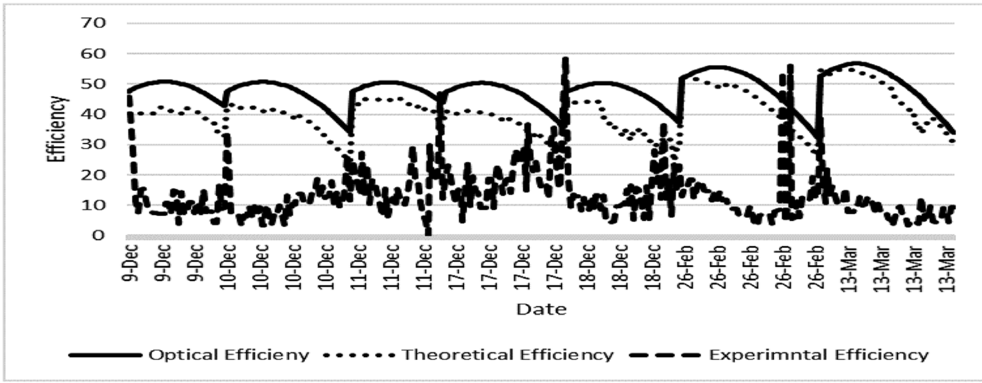
$$\eta_{Energy} = \frac{E_o}{E_i} = \frac{(T_{fw} - T_{iw})\dot{M}C_{pw}}{DNI * \eta_0 * A_{ap} * \Delta t} \tag{4}$$

2.2.2. Exergy efficiency

The exergy efficiency η_{exergy} of the solar cooker can be described as the exergy output Ξ_o associated with fluid in form of increase in temperature to the exergy input Ξ_i associated with solar radiation shown in eq.(13) [13,18]. This analysis provides a quality measure of useful energy that is available for consumption.



2.1: PTC radiation and temperature impact on inlet and outlet fluid along different dates and time



2.2: PTC optical, theoretical and experimental efficiencies along with dates

Fig. 2. PTC Performance parameters Results. (2.1): PTC radiation and temperature impact on inlet and outlet fluid along different dates and time, (2.2): PTC optical, theoretical and experimental efficiencies along with dates.

$$\eta_{exergy} = \frac{\Xi_o}{\Xi_i} = \frac{\frac{\dot{M}C_{pw}\left[\left(T_{fw}-T_{iw}\right)-T_a \ln\frac{T_{fw}}{T_{iw}}\right]}{\Delta t}}{DNI\eta_0\left[1+\frac{1}{3}\left(\frac{T_a}{T_{ss}}\right)^4-\frac{4}{3}\frac{T_a}{T_{ss}}\right]A_{ap}} \quad (5)$$

2.3. Experimental setup and measurements

PTSC specification designed, fabricated, assembled and installed for experimental setup. PTC was made of stainless steel fixed at latitude, absorber pipe made of black painted copper also used as cooker pot, placed at focal line of linear parabolic trough, fluid water carrying field pipe made of mild steel of 88 ft, 20 litters of water tank made of steel and 0.5HP pump for circulating water through the system has been utilized. The temperature of the PTC in receiver pipe on both sides measured manually after every 5 min between 10:30 a.m. to 3:00pm through K type thermocouple. Performance of the cooking system evaluated by developing mathematical models for PTC system and PTC direct cooking through exergy and energy analysis. Finally, experimentation was performed, and data was collected accordingly. The experimental setup of PTC has been shown in Fig. 1.2 and a schematic diagram has been shown in Fig. 1.1 The implementation of model and the performance evaluation results described in graphical form and conclusion of the research proposed.

In this study, three type of sensors were used. One for measuring temperature of K-Type. This was measured against PT100 thermocouple with a hot thermostatic bath model No. WCR-P12 calibration and accuracy ranges from −20 °C to 120 °C and ± 0.01 °C. The other sensor was used to measure solar radiation of model TBS-2-2 Pyrheliometer with the sensitivity of 14 μv/Wm^{-2}. Also, both sensors were pre-calibrated through a lab standard procedure. Mass flow rate was measured using digital transducer S8011R. While, the climate data in which air velocity, dew point, sky temperature, humidity and ambient temperature were collected from Pakistan Metrological Department (PMD). As the experimental data is always associated with some errors. Therefore, uncertainty analysis performed by using Kline and McClintok equation of error propagation [29]. Let x is the function of $y_1, y_2, y_3 \ldots y_n$. The error can be estimated for x by the equation. The experimental uncertainty for theoretical, experimental efficiency, energy efficiency and exergy efficiency found up to ± 2.2%, ± 2.7%, ± 2.4% and ± 2.8% respectively in measured results.

3. Results and discussion

3.1. Performance results of parabolic trough collector

Data collected over 3 months from December to March. It is obvious in Fig. 2.1 to note that as ambient temperature and radiation rises the outlet temperature also rises accordance with inlet temperature and vice versa. Maximum temperature achieved at outlet of parabolic trough was 37.2 °C at 1:20 pm at 33 °C ambient temperature and 838 direct radiation with 0.032 kg/s mass flow rate of 20 L of water. Low temperature raised due to i) ambient temperature and radiation directly impact on overall fluid temperature gain and loss ii) system was not thermally insulated which badly affected the overall performance of parabolic trough.

In Fig. 2.2 comparison of optical, theoretical and experimental efficiencies has been done on different dates and time. It is clear from the results that optical efficiency is always higher than the theoretical and experimental efficiency. It happened because, optical efficiency has no effect of the environmental impacts except clouds and orientations, at fixed latitude. The maximum optical efficiency found at noon ranged between 33 - 53%. The theoretical efficiency calculated ranged between 30 - 50% as it strictly follows the energy input to the system while the experimental efficiency ranged between 5 - 38%. Variation in experimental efficiency was due to system fluid initial temperature at start of experiment found even below than ambient temperature so energy gain by the system becomes high which resulted in high experimental efficiency, but, as soon as, system fluid temperature makes a balance between ambient and operating temperature, efficiency start getting low. It found that as the radiation and ambient temperature rises, theoretical and experimental efficiencies also rise. The difference in experimental and theoretical efficiency found about 12–25%, which is due to the thermal heat losses from conduction to convection within absorber pipe, due to radiation and air convection losses and due to humidity effect, which was not been considered.

3.2. Performance results of energy and exergy analysis of direct PTC solar cooking

Fig. 3.1 describes the water temperature increases as the radiation and ambient temperature raised. Maximum water temperature found in receiver pipe was 53.6 °C at ambient temperature of 31 °C and solar radiation of 927 Wm-2 at 12:00 p.m. sudden fall and rise in fluid temperature was due to fall and rise in solar radiation and ambient temperature. It was also due to partial clouds and cold blow of speedy air as cooker was not thermally insulated.

It is clear in Fig. 3.2 that rise and fall in exergy input and exergy output totally dependent on the water temperature, ambient temperature and radiation. Also, it has been found that as exergy input falls, the exergy output also falls. Also, it has been found that when the fluid temperature reached to a certain point and made a balance with ambient temperature an equilibrium stage establishes, at this stage, if solar radiation starts falling down then fluid temperature also start falling down. It also resulted to take exergy efficiency even go below to zero because, Exergy is an energy that is available for use. After the system and surrounding reach equilibrium, the exergy gets to zero. Negative exergy and energy efficiencies showing that, energy and exergy flows out of system to environment after system and surrounding reached at balance, resulted due to fall of energy and exergy at that state. Negative energy and exergy efficiency values describing loss in efficiency after thermal balance established as energy or exergy flow out of the cooker system.

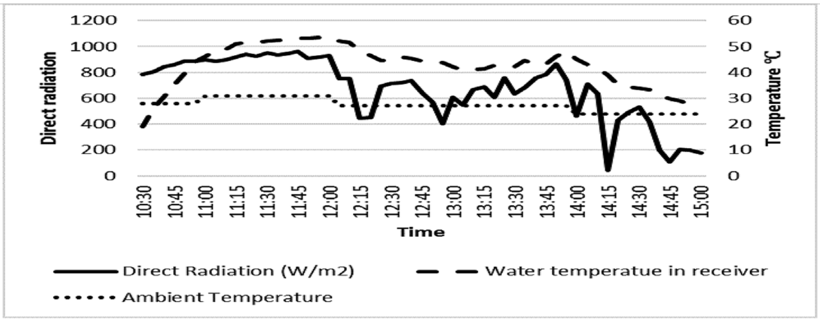
Fig. 3.3, the rise and fall in energy input and energy output totally dependent on the water operating temperature, ambient temperature and solar radiation. In fact, as heat flux coming to the Negative energy output show loss of energy content by water after thermal environmental balance established. Cumulative energy output found in range between 0.98 and 6.8 kJ to and energy input found in range between 168 and 17461 kJ in 5 min. It has been found that as energy input decreases the energy output also drops down.

Fig. 3.4 describes the energy efficiency and exergy efficiency along with time, as the energy efficiency increase and decreases, the exergy efficiency also raises and drops down. The solar cooker energy efficiency found in range between "0.11–7%" and exergy efficiency found in range between 2.1×10^{-2} - 7.6×10^{-2}%. These low efficiencies are in agreement with literature [13,30]. The rise and fall of the efficiency was due to equilibrium between pipe temperature and ambient temperature. This equilibrium affected thermal efficiency of fluid to decreases or increase as the fluid temperature decreases or increase along with rise and fall of ambient temperature and solar radiation. The exergetic analysis results are useful in making evaluation of design and performance of the system in terms of useful energy. This analysis depicts where the quality energy is being consumed and how much is available for use. The main energy losses are due to wild winter condition that dissipate the energy found on the collector. So, the sizing and design of the reflector estimated accordance with exergetic analysis and resulted temperature of the system.

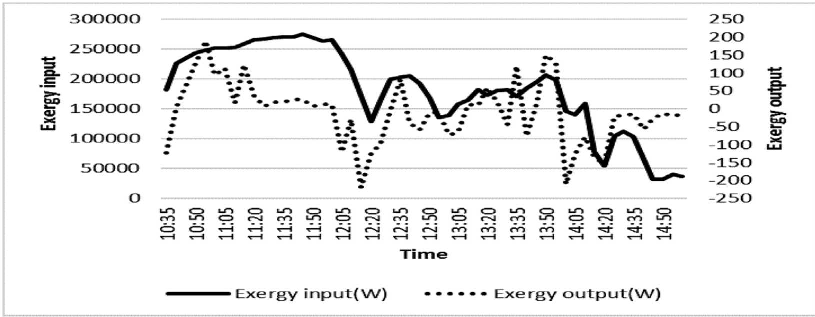
4. Conclusion

In this study:

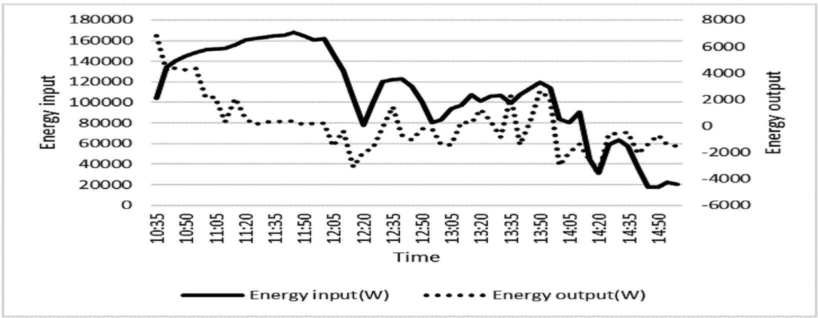
i. The performance of solar cooking using parabolic trough has been determined theoretically and experimentally in terms of energy and exergy analysis.



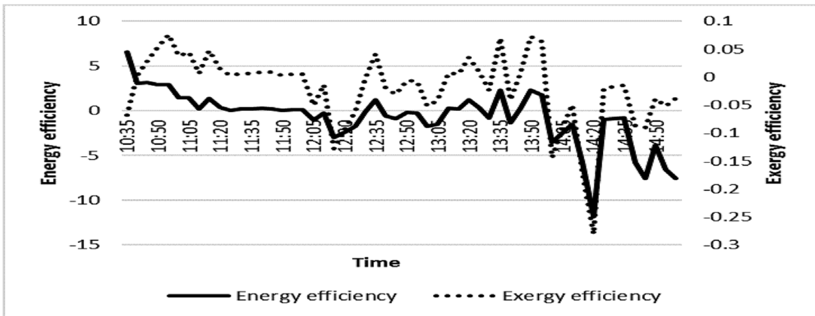
3.1: PTSC Direct radiation, ambient temperature of and fluid temperature along time



3.2: PTSC Exergy input and exergy output along with time



3.3: PTSC Energy input and energy output along with time



3.4: PTSC Energy and exergy efficiency along with time

Fig. 3. PTSC Performance parameters of the experimental Results. (3.1): PTSC Direct radiation, ambient temperature of and fluid temperature along time, (3.2): PTSC Exergy input and exergy output along with time, (3.3): PTSC Energy input and energy output along with time, (3.4): PTSC Energy and exergy efficiency along with time.

ii. PTC achieved maximum temperature 37.2 °C of 20-L water tank at 1:20 pm at 33 °C ambient temperature and 838 direct radiation. PTSC direct cooking maximum water temperature found in collector was 53.6 °C at ambient temperature of 31 °C and solar radiation of 927 Wm-2 at 12:00 p.m.

iii. To make cooking requirements fulfill in such a wild winter conditions for sizing and better efficiency, aperture area of PTC should be considered up to six to seven time larger than existing size almost $7m^2$ to achieve to 300 °C.

Nomenclature

A_{ap}	Aperture trough Area (m^2)
A_f	Geometrical reduction factor, (−)
A_{re}	External area of receiver, (m^2)
A_{ri}	Inside receiver surface area, (m^2)
C	Concentration ratio (−)
C_p	Specific heat of fluid at constant pressure, ($kJkg^{-1}K^{-1}$)
C_{pw}	Specific heat of the fluid at mean temperature, ($kJkg^{-1}K^{-1}$)
DI	Direct irradiance, (Wm^{-2})
DNI	Direct Normal Incidence, (Wm^{-2})
d_{re}	Receiver pipe external diameter, (m)
d_{ri}	Receiver pipe internal diameter, (m)
E_i	Energy input, (W)
E_o	Energy output, (W)
Ξ_i	Exergy input, (W)
Ξ_o	Exergy output, (W)
f	Focal length, (m)
f_r	Frictional factor in receiver, (m)
H	Global efficiency, (−)
L_r	Length of receiver pipe, (m)
L_c	Parabolic trough length, (m)
$\dot{M}$	Mass in receiver pipe, (kg)
$\dot{m}$	Fluid mass flow rate, (kgs^{-1})
$Q_{rad,\ ca}$	Heat of radiation transfer from sky to receiver, (W)
Q_f	Heat content by the fluid, (W)
Q_l	Collector overall heat loss factor, ($W\ m^{-2}K^{-1}$)
Q_r	Heat removal factor, (−)
T_a	Ambient average temperature, (K)
T_f	Fluid average/mean temperature, (K)
$T_{f,\ in}$	Fluid inlet temperature, (K)
$T_{f,\ o}$	Fluid outlet temperature, (K)
T_{fw}	Water temperature after time Δt , (K)
T_{iw}	Initial temperature before time Δt , (K)
T_{re}	Receiver pipe external surface temperature, (K)
T_{ri}	Receiver pipe internal surface temperature, (K)
T_{ss}	Solar surface temperature on earth surface, (K)
Δt	Time between two consecutive fluid temperature measurements, (minutes)
W_c	Width of parabolic trough, (m)
α_r	Absorptance of the receiver, (−)
γ	Instantaneous intercept factor (faction of rays that fall upon the receiver aperture for the specific incident angle), (−)
$\in_r$	Receiver emissivity, (−)
η_{Energy}	Energy efficiency, (−)
θ	Angle of incidence of sun ray on the collector aperture, (rad)
ϑ_o	Receiver rim angle (rad)
λ_r	Receiver pipe thermal conductance for copper, ($W\ m^{-1}K^{-1}$)
ρ_c	Average specular reflectance of the reflector, (−)
ϱ_r	Receiver roughness factor (−)

Conflicts of interest

Authors declare no conflict of interests regarding this paper.

References

[1] A. Ghafoor, et al., Current status and overview of renewable energy potential in Pakistan for continuous energy sustainability, Renew. Sustain. Energy Rev. 60 (2016) 1332–1342.
[2] N. Mejriszan Toosi, J.A. Esfahani, M. Reza Safaei, Investigation of energy consumption and renewable energy resources in top ten countries with most energy

consumption, IOP Conf. Ser. Mater. Sci. Eng. 397 (2018) 012108.
[3] U. Qazi, et al., An institutional framework for the development of sustainable and competitive power market in Pakistan, Renew. Sustain. Energy Rev. 70 (2017) 83–95.
[4] Z.R. Tahir, M. Asim, Surface measured solar radiation data and solar energy resource assessment of Pakistan: a review, Renew. Sustain. Energy Rev. 81 (2018) 2839–2861.
[5] B. Akhtar, et al., Determinants of deposits in conventional and Islamic banking: a case of an emerging economy, Int. J. Emerg. Mark. 12 (2) (2017) 296–309.
[6] HDIP, Pakistan Energy Year Book, (2014) [cited 2014 20 December]; Available from: http://www.hdip.com.pk/contents/Energy-Yearbook-2012-Available/32.html.
[7] G.K. Manikandan, S. Iniyan, R. Goic, Enhancing the optical and thermal efficiency of a parabolic trough collector – a review, Appl. Energy 235 (2019) 1524–1540.
[8] R. Wang, et al., Experimental performance of 300 kWth prototype of parabolic trough collector with rotatable axis and irreversibility analysis, Energy 161 (2018) 595–609.
[9] A. Herez, M. Ramadan, M. Khaled, Review on solar cooker systems: economic and environmental study for different Lebanese scenarios, Renew. Sustain. Energy Rev. 81 (2018) 421–432.
[10] J. Khan, M.H. Arsalan, Solar power technologies for sustainable electricity generation–A review, Renew. Sustain. Energy Rev. 55 (2016) 414–425.
[11] E. Cuce, P.M. Cuce, A comprehensive review on solar cookers, Appl. Energy 102 (0) (2013) 1399–1421.
[12] G.M. Mufti, et al., Performance analysis of parabolic trough collectors for Pakistan using mathematical and computational models, 2016 Clemson University Power Systems Conference (PSC), IEEE, 2016.
[13] H.H. Öztürk, Experimental determination of energy and exergy efficiency of the solar parabolic-cooker, Sol. Energy 77 (1) (2004) 67–71.
[14] M. Aramesh, et al., A review of recent advances in solar cooking technology, Renew. Energy 140 (2019) 419–435.
[15] H. Olia, et al., Application of nanofluids in thermal performance enhancement of parabolic trough solar collector: state-of-the-art, Appl. Sci. 9 (3) (2019) 463.
[16] M. Goodarzi, et al., Investigation of nanofluid mixed convection in a shallow cavity using a two-phase mixture model, Int. J. Therm. Sci. 75 (2014) 204–220.
[17] S. Indora, T.C. Kandpal, Institutional and community solar cooking in India using SK-23 and Scheffler solar cookers: a financial appraisal, Renew. Energy 120 (2018) 501–511.
[18] S.K. Sansaniwal, V. Sharma, J. Mathur, Energy and exergy analyses of various typical solar energy applications: a comprehensive review, Renew. Sustain. Energy Rev. 82 (2018) 1576–1601.
[19] N. Kumar, G. Vishwanath, A. Gupta, An exergy based unified test protocol for solar cookers of different geometries, Renew. Energy 44 (2012) 457–462.
[20] A. Pandey, et al., Comparative experimental study of solar cookers using exergy analysis, J. Therm. Anal. Calorim. 109 (1) (2011) 425–431.
[21] N. Kumar, G. Vishwanath, A. Gupta, An exergy based test protocol for truncated pyramid type solar box cooker, Energy 36 (9) (2011) 5710–5715.
[22] H.H. Ozturk, Comparison of energy and exergy efficiency for solar box and parabolic cookers, J. Energy Eng. 133 (1) (2007) 53–62.
[23] T.A. Yassen, Experimental and theoretical study of a parabolic trough solar collector, Anbar J. Eng. Sci. 5 (1) (2012) 109–125.
[24] Y.A. Cengel, J.M. Cimbala, Fluid Mechanics vol. 1, Tata McGraw-Hill Education, 2006.
[25] G. Coccia, G. Latini, M. Sotte, Mathematical modeling of a prototype of parabolic trough solar collector, J. Renew. Sustain. Energy 4 (2) (2012) 023110.
[26] A. Abd-ennour, et al., Mathematical modelling of a solar parabolic trough collector, International Journal of Engineering Research and Technology, ESRSA Publications, 2015.
[27] J.A.D.a.W.A. Beckman, Solar Engineering of Thermal Processes, John Wiley & Sons, 2006.
[28] C. Tzivanidis, et al., Thermal and optical efficiency investigation of a parabolic trough collector, Case Studies in Thermal Engineering, vol. 6, 2015, pp. 226–237.
[29] J. Holman, Experimental Methods for Engineers, eighth ed., McGraw-Hill Series, 2011 Mechanical Engineering.
[30] R. Petela, Exergy analysis of the solar cylindrical-parabolic cooker, Sol. Energy 79 (3) (2005) 221–233.