BNUT

Iranica Journal of Energy and Environment

Journal Homepage: www.ijee.net

IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

Comparative Exergy, Economic and Environmental Analysis of Parabolic Trough Collector and Linear Fresnel Reflector

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P A P E R   I N F O

Paper history:
Received 01 August 2023
Accepted in revised form 13 September 2023

Keywords:
Cost
Efficiency
Exergy destruction
Mass flow rate
Solar collector
Solar radiation

A B S T R A C T

In recent years, the use of renewable energy sources and investigation on renewable energy have significantly grown. In this research, parabolic trough and linear Fresnel collectors, which are widely used in the field of solar energy, have been investigated from the point of view of exergy. First, the energy balance equations for different components of the collector were solved using numerical methods and the temperature distribution in each component of the collector was obtained. Then the values of exergy destruction in each component of the system were calculated. The comparison of the results obtained in the present work with the results of the previous research showed a good agreement. The results showed that the exergy efficiency in the parabolic trough collector is approximately 1.5 times that of the linear Fresnel reflector. Also, changes in exergy efficiency, exergy destruction of the whole collector, output exergy cost and CO_2 emission with increasing solar radiation intensity and fluid mass flow rate for both collectors have been compared and investigated.

***Doi**: 10.5829/ijee.2024.15.02.07*

NOMENCLATURE

A	Area (m^2)
C_C	Cost of installation of collector (\$/m^2)
C_E	Cost of output exergy (\$/kWh)
C_{HTF}	Cost of heat transfer fluid (\$/m^2)
C_I	Initial cost (\$/kWh)
C_{MO}	Cost of operation and maintenance (\$/kWh)
C_P	Heat capacity (j/kg.K)
D	Diameter (m)
E	Exergy rate (W)
F_R	Heat removal factor
F'	Efficiency factor
f_w	Friction coefficient of pipe wall
G_B	Solar direct beam irradiation (W/m^2)
h_c	Convection heat transfer coefficient (W/m^2.K)
h_r	Radiation heat transfer coefficient (W/m^2.K)
I	Coefficient of equipment life
i	Interest rate (%)

Subscripts

a	Environmental
air	Ait
ave	Average
$change$	Change
$cold$	Cold
dst	Destruction
f	Fluid
$fuel$	Fuel (used for inlet exergy)
g	Glass cover
gi	Inner wall of glass cover
go	Outer wall of glass cover
hot	Hot
i	Inner wall of absorber tube
$loss$	Loss
net	Net
o	Outeer wall of absorber tube

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Please cite this article as: M. Maghsoudizadeh, M. Ameri, E. Jahanshahi Javaran, A. Motamedsadr and A. A. Feili Monfared, 2024. Comparative Exergy, Economic and Environmental Analysis of Parabolic Trough Collector and Linear Fresnel Reflector, Iranica Journal of Energy and Environment, 15(2), pp.177-186. Doi: 10.5829/ijee.2024.15.02.07

K	Conductivity (W/m.K)	opt	Optical
L	Length of collector (m)	out	Out
$\dot{m}$	Mass flow rate (kg/s)	ov	Overal
n	Life time (year)	$pump$	Pump
Nu	Nusselt number	r	Absorber tube
p	Absolute pressure (Pa)	ref	Reflector
Pr	Prandtl number	sun	Sun
Q	Heat transfer rate (W)	th	Thermal
Re	Reynolds number	in	Input to the collector
T	Density (kg/m^3)	u	Useful
T	Temperature (K)	**Greek Symbols**	
U	Heat transfer coefficient (W/m^2.K)	α	Density (kg/m^3)
V	Velocity (m^2/s)	γ	Lattice time step
V_∞	Wind velocity (m^2/s)	ε	Kinematic viscosity (m^2/s)
W_a	Width of collector (m)	η	Density (kg/m^3)
x_{CO2}	The amount of carbon dioxide released at the considered time (kg/h)	μ	Lattice time step
y_{CO2}	The amount of carbon dioxide emission of the reference energy system (kg/h)	ρ	Kinematic viscosity (m^2/s)
		ρ_{ref}	Density (kg/m^3)
		σ	Lattice time step
		τ	Kinematic viscosity (m^2/s)

INTRODUCTION

The sun is a huge glowing sphere that provides light and heat in the middle of solar system. Almost all energy resources on earth are originated from the sun and recently, with the introduction of energy supply from renewable sources, the direct use of solar energy to generate electricity has received much attention. In order to provide electricity from the sun, two main methods have been proposed: 1. Direct conversion of solar energy into electricity. 2. Transferring solar heat to the operating fluid of a power generation cycle. The first method is the basis of photovoltaic systems. In the second method, an equipment called a solar collector is used. Solar collectors collect sunlight and concentrate it on a point or a line. The heat from concentrated radiation is transferred to a fluid. This method is called solar thermal energy. The most famous solar power collectors, which focus sunlight on a line, are parabolic trough and collectors and linear Fresnel reflectors. Figures 1 and 2 show the schematic images of these collectors.

So far, many theoretical and experimental researches have been done on parabolic trough and linear Fresnel collectors, some of which are mentioned below. In 2000, Singh et al. [1] investigated solar thermal systems including parabolic trough collectors for Rankine cycle power plants based on energy and exergy perspectives. In 2007, Tyagi et al. [2] investigated the energy and exergy efficiencies of parabolic trough collector for very low and high mass flow rates. In 2012, Reddy et al. [3] evaluated

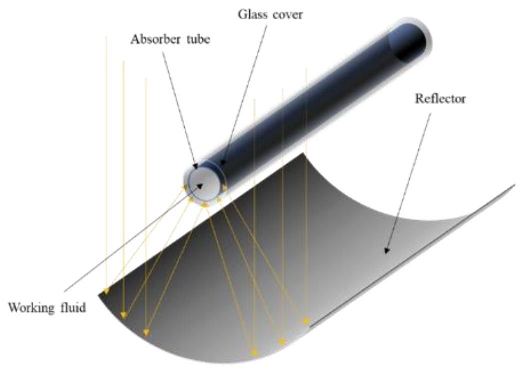

Figure 1. Schematic of a parabolic trough collector

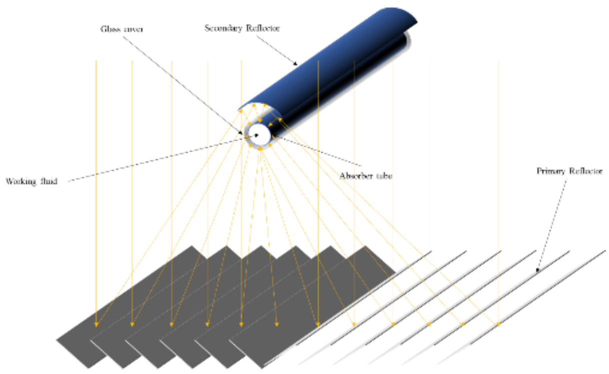

Figure 2. Schematic of a linear Fresnel reflector

the energy and exergy of parabolic trough collectors for variable radiation in different cities of India. The results showed that the maximum exergy for different places is obtained at different times. In 2016, Kulkarni [4] designed and fabricated a cylindrical parabolic trough collector covered with a glass coating and found the instantaneous efficiency of it to be 66%. In 2017, Bellos et al. [5] performed exergy analysis for parabolic trough collectors with different fluids and compared the results. In this research, the effect of fluid inlet temperature change on exergy destruction and energy efficiency was investigated. In 2018, Allouhi et al. [6] performed an exergy analysis for a parabolic collector by adding nanoparticles to the working fluid. The results obtained in this research indicate that addition of nanoparticles to the fluid significantly improves the performance of the collector from the exergy point of view. In 2018, Bellos et al. [7] investigated the performance of a linear Fresnel reflector using three different fluids from energy and exergy perspectives. In this research, the effect of fluid inlet temperature change on exergy destruction and energy efficiency was investigated. In 2019, Roostaee and Ameri [8] performed exergy analysis for different arrangements of linear Fresnel focusing mirrors and compared the results. In 2019, Lopez et al. [9] conducted a comparative study between parabolic trough and linear Fresnel collector for a sugarcane factory with simultaneous power cogeneration. In this research, it was shown that if a parabolic trough collector is used, the annual exergy efficiency is about 35% higher than a linear Fresnel reflector. In 2023 Mahmoudi et al. [10] analyzed a multigeneration system included nanofluid-based parabolic trough collector integrated with a quadruple effect absorption refrigeration cycle (cooling), a thermoelectric generator (power), a PEM electrolyzer (hydrogen), vapor generator and domestic water heater. The system power generation was 18.78 kW and energy and exergy efficiency of the collector was 82.21% and 80.48%, respectively.

In the present study, a parabolic trough collector and a linear Fresnel reflector in steady operating condition were studied and the effect of changing the intensity of solar radiation and fluid mass flow rate on them was investigated. Finally, their results were compared with each other from the point of view of exergy, economy and environment.

MATERIAL AND METHODS

As can be seen in Figures 1, 2 and 3, parabolic trough collectors (PTC) and linear Fresnel reflectors (LFR) have four main components: 1. reflective plate or plates 2. glass cover 3. absorber tube (Receiver) 4. working fluid.

The reflector in the PTC is a parabolic mirror. In constructing this mirror, the smallest errors cause the reflected beam to deviate and not reach the absorber. Therefore, its design and construction required great precision. In the LFR, the reflecting plates are a number of narrow linear mirrors, each of which has a certain width and a certain horizontal distance from the center of the reflector. The glass cover is a cylinder envelope with a circular cross-section, inside which the absorber tube is placed. The distance between the glass cover and the absorber tube is vacuumed. The absorber tube is also a cylindrical tube with a circular cross-section an its material is mainly galvanized steel and the working fluid passes through it.

The working mechanism of both collectors is that first the reflector receives the solar radiation and reflects it on a line. The absorber tube, which exactly corresponds to the said line, absorbs the reflected radiation and transfers it to the fluid inside the tube. It should be noted that all the radiation reflected from the reflector does not reach the glass cover and then the absorber tube. This issue may occur due to the improper design of the parabola or the improper distance of the absorber tube from the surface of the reflector in the parabolic trough collector. In linear Fresnel reflectors, the dimensions and location of the mirrors, the height of the absorber tube, etc., cause a part of the reflected radiation not to hit the absorber tube and leave the collector. On the other hand, the non-perpendicular angle of sunlight entering the collector aperture may also increase this problem. In this way, a parameter called intercept factor is defined. The intercept factor is the ratio of the radiation reaching the glass cover to the total radiation reflected from the reflector surface. In fact, the main difference between parabolic trough and linear Fresnel collectors in their governing equations is in the value of their intercept factor. Various factors affect the value of the intercept factor of a collector. For example, the parabolic geometry in the parabolic trough collector, the dimensions and location of the mirrors in the linear Fresnel reflector, and the focal distance of the collector are among the factors that affect the intercept factor of parabolic trough and linear Fresnel collectors.

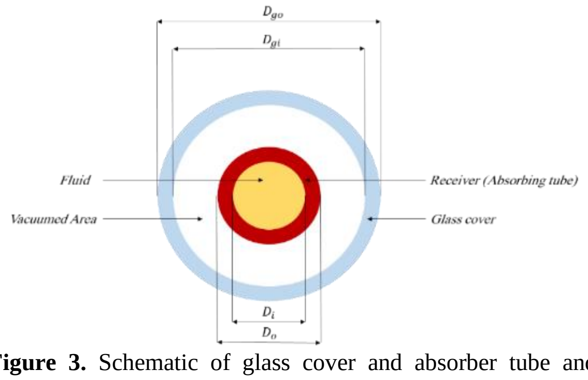

Figure 3. Schematic of glass cover and absorber tube and working fluid

Also, the angle of sunlight entering the collector aperture is one of the most important factors influencing the interception coefficient. In fact, the best situation for a collector is that the sun's rays enter perpendicularly to the aperture of the collector. But these rays often enter the collector obliquely, which causes a decrease in the intercept factor. As mentioned before, parabolic trough and linear Fresnel collectors have a similar construction. Therefore, the energy conservation equations are the same for both and the main difference is in the data values that are replaced. For modeling, energy conservation equations of different components have been written and the resulting equations have been solved using numerical methods. The assumptions used to write energy equations are [5, 7]:

1. Due to small diameter of the absorber tube compared to its length, it is assumed that the temperature of the fluid changes only in the flow direction and there is no temperature gradient along the radius.
2. The solar collector works under steady conditions.
3. The sun's rays enter the collector aperture perpendicularly. The purpose of this assumption is that the intercept factor is the highest possible value and the negative effect caused by the angularity of the incoming solar radiation is removed from the results.
4. The sky temperature (for radiative heat transfer) and the ambient air temperature (for convective heat transfer) are assumed to be the same.
5. Since the absorption coefficient of the glass surface is very small compared to its transmission coefficient, the absorption of radiation on the surface of the glass cover is neglected.

The energy conservation equations for the inner and outer surfaces of the absorber tube and the glass cover and the fluid are given in the form of equations 1 to 5.

Energy conservation equation for the outer surface of the absorber tube [11, 12]:

$$\tau\alpha\rho_{ref}G_B\ A_c + A_o\ h_{r,o-gi}\left(T_{gi}-T_o\right) + A_o\ \frac{(2k_r)}{D_o ln\left(\frac{D_o}{D_i}\right)}(T_i-T_o)=0 \quad for\ PTC$$
$$\tau\alpha\rho_{ref1}\rho_{ref2}G_B\,A_c + A_o\,h_{r,o-gi}\left(T_{gi}-T_o\right) + A_o\,\frac{2k_r}{D_o ln\left(\frac{D_o}{D_i}\right)}(T_i-T_o)=0 \quad for\ LFR \tag{1}$$

Of course, it should be noted that because in the LFR, a secondary reflector is used in addition to the main reflector, in the first term of equation 1, instead of ρ_{ref}, the term $\rho_{ref1}\rho_{ref2}$ should be replaced.

Energy conservation equation for the inner surface of the absorber tube [11, 12]:

$$\frac{2k_r}{D_o ln\left(\frac{D_o}{D_i}\right)}(T_o-T_i) + \frac{D_i}{D_o}h_{c,f-i}\left(T_f-T_i\right)=0 \tag{2}$$

Energy conservation equation for the outer surface of the glass cover [11, 12]:

$$\frac{2k_g}{D_{go}\ \ ln\left(\frac{D_{go}}{D_{gi}}\right)}\left(T_{gi}-T_{go}\right) + \left(h_{r,go-a}+h_{c,go-a}\right)\times \left(T_a-T_{go}\right)=0 \tag{3}$$

Energy conservation equation for the inter surface of the glass cover [11, 12]:

$$A_o h_{r,o-gi}\left(T_o-T_{gi}\right) + \frac{2k_g}{D_{go}\ln\left(\frac{D_{go}}{D_{gi}}\right)}A_{go}\left(T_{go}-T_{gi}\right)=0 \tag{4}$$

Energy conservation equation for the fluid [11, 12]:

$$A_i h_{c,f-i}\left(T_i-T_f\right) + \dot{m}c_p\left(T_{in}-T_{out}\right)=0 \tag{5}$$

The heat loss coefficient between the absorber tube and the outside environment and the total heat coefficient of the collector are calculated from relations 6 and 7 [11, 12]:

$$U_{Loss}=\left(\frac{1}{h_{r,o-gi}}+\frac{D_o\ ln\left(\frac{D_{go}}{D_{gi}}\right)}{2k_g}+\frac{D_o}{D_{go}}\ \frac{\mathbf{1}}{\left(h_{c,go-a}+h_{r,go-a}\right)}\right)^{-1} \tag{6}$$

$$U_{ov}=\left(\frac{1}{U_{Loss}}+\frac{D_o}{h_{c,f-i}D_i}+\frac{D_o\,ln(D_o/D_i)}{2k_r}\right)^{-1} \tag{7}$$

The radiation heat transfer coefficients are calculated from relations 8 and 9 [11, 12]:

$$h_{r,go-a}=\varepsilon_g\sigma\left(T_{go}+T_a\right)\left({T_{go}}^2+{T_a}^2\right) \tag{8}$$

$$h_{r,o-gi}=\frac{\sigma\left({T_o}^2+{T_{gi}}^2\right)\left(T_o+T_{gi}\right)}{\frac{1}{\varepsilon_r}+\frac{A_o}{A_{go}}\left(\frac{1}{\varepsilon_g}-1\right)} \tag{9}$$

Nusselt number (Nu) and heat transfer coefficient for flow over cylindrical tubes are calculated from relations 10 to 12 [12, 13]:

$$Nu=0.4+0.54(Re_D)^{0.52}\quad for\quad Re<1000$$
$$Nu=0.3(Re)^{0.6}\quad for\quad 1000<Re<50000 \tag{10}$$

$$Re_D=\frac{\rho_{air}\,V_\infty\,D_{go}}{\mu_{air}} \tag{11}$$

$$h_{c,go-a}=\frac{k_{air}\,Nu}{D_{go}} \tag{12}$$

For fully developed turbulent flow in smooth pipes, Nusselt number (Nu) and heat transfer coefficient are calculated from relations 13 to 15 [12, 13]:

$$Nu=0.023\,{Re_D}^{0.8}\,Pr^{0.4} \tag{13}$$

$$Re_D=\frac{4\dot{m}}{\pi\,D_i\,\mu_f} \tag{14}$$

$$h_{c,f-i}=\frac{k_f\,Nu}{D_i} \tag{15}$$

According to equation 16, the thermal efficiency is defined as the ratio of the energy absorbed by the working fluid to the total direct radiant energy entering the collector aperture:

$$\eta_{th} = \frac{Q_u}{A_c\, G_B} \tag{16}$$

In equation 16, Q_u is the thermal energy absorbed by the working fluid, whose value is obtained from two relations 17 and 18 [11, 13]:

$$Q_u = F_R\left[G_B\, \eta_{opt}\, A_c - A_o\, U_{Loss}(T_{in} - T_a)\right] \tag{17}$$

$$Q_u = \dot{m}c_p(T_{out} - T_{in}) \tag{18}$$

The optical efficiency of the collector (η_{opt}) is calculated from equation 19. It is necessary to explain that the difference between PTC and LFR is in the calculation of this value [11]:

$$\begin{aligned} &\eta_{opt} = \rho_{ref}\tau\alpha\gamma \quad for \quad PTC \\ &\eta_{opt} = \rho_{ref1}\rho_{ref2}\tau\alpha\gamma \quad for \quad LFR \end{aligned} \tag{19}$$

The collector heat removal factor (F_R) and the efficiency factor (F') are calculated from equations 20 and 21 [11]:

$$F_R = \frac{\dot{m}c_p}{A_o U_{Loss}}\left[1 - exp^{\left(-\frac{U_{Loss}F' A_o}{\dot{m}c_p}\right)}\right] \tag{20}$$

$$F' = \frac{U_{ov}}{U_{Loss}} \tag{21}$$

Exergy is the most useful work that can be obtained from a system in a process until reaching thermodynamic equilibrium. Therefore, to determine the part of thermal energy that can be converted into useful work under ideal conditions, the exergy analysis of the system is required. Exergy change in a solar collector takes place in two ways: 1. heat transfer 2. fluid flow.

Exergy with incompressible fluid flow at temperature T and pressure p is expressed by equation 22 [14]:

$$\dot{E}_f = \dot{m}c_p\left(T - T_a - T_a\, ln\frac{T}{T_a}\right) + \frac{\dot{m}_f\,(p - p_a)}{\rho} + \frac{\dot{m}\,V^2}{2} \tag{22}$$

Equation 23 is used to calculate the exergy exchanged through heat transfer $\dot{Q}$ between two sources with hot temperature T_{hot} and cold temperature T_{cold} [15]:

$$\dot{E}_{\dot{Q}} = \int_{T_{cold}}^{T_{hot}} \dot{Q}\,\frac{T_a}{T^2}\,dT \tag{23}$$

The balance of exergy in steady state is written as equation 24:

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} - \sum \dot{E}_{loss} - \sum \dot{E}_{dst} = 0 \tag{24}$$

According to equation 24, in steady state, two things happen for the exergy input to a system and the rest leaves the system as useful outlet exergy: 1. A part of the exergy is wasted in the exchange with the surrounding environment ($\dot{E}_{loss}$). 2. Some of it is destroyed by the system components ($\dot{E}_{dst}$).

The input exergy to the collector includes the input exergy by fluid flow and the exergy rate related to solar radiation, which can be calculated from relations 25 to 27 [14, 16]:

$$\sum \dot{E}_{in} = \dot{E}_{in,f} + \dot{E}_{in,sun} \tag{25}$$

$$\dot{E}_{in,f} = \dot{m}\, c_p\left(T_{in} - T_a - T_a\, ln\left(\frac{T_{in}}{T_a}\right)\right) + \frac{\dot{m}(p_{in} - p_a)}{\rho} + \frac{\dot{m}\,V_{in}^2}{2} \tag{26}$$

$$\dot{E}_{in,sun} = G_B A_c\left(1 - \frac{4}{3}\frac{T_a}{T_{sun}} + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4\right) \tag{27}$$

The output exergy rate is equal to the exergy rate by the fluid flow and its value is obtained from the following equation:

$$\sum \dot{E}_{out} = \dot{E}_{out,f} = \dot{m}c_p\left(T_{out} - T_a - T_a\, ln\left(\frac{T_{out}}{T_a}\right)\right) + \frac{\dot{m}\,(p_{out} - p_a)}{\rho} + \frac{\dot{m}\,V_{out}^2}{2} \tag{28}$$

On the other hand, the loss exergy rate only includes the loss heat rate from the glass cover to the environment, which is shown in equation 29:

$$\sum \dot{E}_{loss} = \dot{E}_{loss,g-a} = \int_{T_a}^{T_{go}} \dot{Q}_{loss}\,\frac{T_a}{T^2}\,dT \tag{29}$$

Exergy destruction of the collector, including exergy destruction due to the temperature difference between the absorber tube and the sun, the inside and outside of the absorber tube, the absorber tube and the fluid through it, the absorber tube and the glass cover, the inside and outside of the glass cover, and the resulting optical destruction. Factors such as concentrator, absorbent tube and glass cover ingredients, errors in construction and installation of the collector, and errors in tracking the sun, which are shown by relations 30 to 38:

$$\sum \dot{E}_{dst} = \dot{E}_{dst,opt,ref} + \dot{E}_{dst,opt,g} + \dot{E}_{dst,r-g} + \dot{E}_{dst,g} + \dot{E}_{dst,opt,r} + \dot{E}_{dst,r-sun} + \dot{E}_{dst,r} + \dot{E}_{dst,f-r} \tag{30}$$

$$\begin{aligned} &\dot{E}_{dst,opt,ref} = \left(1 - \gamma\,\rho_{ref}\right)\dot{E}_{in,sun} \quad for \quad PTC \\ &\dot{E}_{dst,opt,ref} = \left(1 - \gamma\,\rho_{ref1}\rho_{ref2}\right)\dot{E}_{in,sun} \quad for \quad LFR \end{aligned} \tag{31}$$

$$\begin{aligned} &\dot{E}_{dst,opt,gla} = \gamma\,\rho_{ref}(1 - \tau)\dot{E}_{in,sun} \quad for \quad PTC \\ &\dot{E}_{dst,opt,gla} = \gamma\,\rho_{ref1}\,\rho_{ref2}(1 - \tau)\dot{E}_{in,sun} \quad for \quad LFR \end{aligned} \tag{32}$$

$$\begin{aligned} &\dot{E}_{dst,opt,r} = \tau\,\gamma\,\rho_{ref}(1 - \alpha)\dot{E}_{in,sun} \quad for \quad PTC \\ &\dot{E}_{dst,opt,r} = \tau\,\gamma\,\rho_{ref1}\,\rho_{ref2}(1 - \alpha)\dot{E}_{in,sun} \quad for \quad LFR \end{aligned} \tag{33}$$

$$\dot{E}_{dst,r-g} = \int_{T_{gi}}^{T_{ro}} \dot{Q}_{loss}\,\frac{T_a}{T^2}\,dT \tag{34}$$

$$\dot{E}_{dst,g} = \int_{T_{go}}^{T_{gi}} \dot{Q}_{loss}\,\frac{T_a}{T^2}\,dT \tag{35}$$

$$\dot{E}_{dst,r-sun} = \int_{T_{ro}}^{T_{sun}} \eta_{opt} G_B A_c\,\frac{T_a}{T^2}\,dT \tag{36}$$

$$\dot{E}_{dst,r} = \int_{T_{ri}}^{T_{ro}} \dot{Q}_u \frac{T_a}{T^2}\, dT \quad (37)$$

$$\dot{E}_{dst,f-r} = \int_{T_f}^{T_{ri}} \dot{Q}_u \frac{T_a}{T^2}\, dT \quad (38)$$

In equation 38, T_f is calculated by relation 39 [12]:

$$T_f = \frac{T_{out}-T_{in}}{\ln\left(\frac{T_{out}}{T_{in}}\right)} \quad (39)$$

In these collectors, a pump is used to compensate the pressure drop. In fact, the pump makes the fluid inlet and outlet pressure the same. Therefore, it can be concluded that for the input pressure of the fluid to the collector, the power consumption of the pump, the pressure drop, the average speed of the fluid and the friction coefficient are calculated from the equations 40 to 44 [17]:

$$p_{in} = p_{out,pump} \quad (40)$$

$$\dot{w}_{pump} = \frac{\dot{m}\,\Delta p}{\rho\,\eta_{pump}} \quad (41)$$

$$\Delta p = \frac{f_w\, L\, \rho\, V_{ave}^{\ 2}}{2D_i} \quad (42)$$

$$V_{ave} = \frac{4\dot{m}}{\pi\rho D_i^{\ 2}} \quad (43)$$

$$f_w = \frac{0.316}{Re^{0.25}} \quad (44)$$

It is necessary to explain that in this research, the efficiency of the pump (η_{pump}) is considered to be 85% [5]. Now, to calculate the exergy destruction rate caused by the pump work, equation 45 can be used [12]:

$$\dot{E}_{dst,pump} = \frac{T_a}{T_f}\, \dot{w}_{pump} \quad (45)$$

So, the net useful exergy of fluid flow can be calculated from equation 46:

$$\dot{E}_{u,net} = \dot{E}_{in,sun} - \sum \dot{E}_{dst} - \sum \dot{E}_{loss} - \dot{E}_{dst,pump} \quad (46)$$

Finally, the exergy efficiency of the collectors is calculated using equation 47:

$$\eta_{ex} = \frac{\dot{E}_{u,net}}{\dot{E}_{in}} \quad (47)$$

To find the cost of each kilowatt hour of useful output exergy from collector (C_E) equations 48 to 51 and Table 1 are used [18].

$$C_E = C_I + C_{MO} \quad (48)$$

$$C_I = \frac{(C_{HTF}+C_C)I}{8760\times\dot{E}_{out}} \quad (49)$$

$$I = \frac{i(i+1)^n}{(i+1)^n-1} \quad (50)$$

$$C_{MO} = 0.06\, C_I \quad (51)$$

Table 1. Economic parameters [18-20]

Parameter	Unit	PTC	LFR
C_{HTF}	$\frac{\$}{m^2}$	28.35	28.35
C_C	$\frac{\$}{m^2}$	148	1819
n	$year$	20	20
i	%	2	2

At last, the rate of CO_2 release for each collector (x_{CO2}) is calculated from equation 52. In this relation, the amount of carbon dioxide emission of the reference energy system (y_{CO2}) is equal to 0.00647 kg [18].

$$x_{CO2} = y_{CO2}\, \dot{E}_{out} \quad (52)$$

RESULTS AND DISCUSSION

Now, in order to solve, the length of the collector is divided into a number of volumetric elements. First, the temperatures of fluid, absorber tube and glass cover are guessed for each element. Then the energy equations are solved to calculate the temperature distribution and after that the obtained temperatures were compared with the guessed temperatures. If the difference between the calculated values and the initial guess of temperatures are less than 0.001, the solution is converged and acceptable. Otherwise, the calculated temperatures should be considered as a new guess and the solution process should be repeated until the correct answer is reached. In order to check the accuracy of the written code, the results of this research were compared with the results of the work of Bellos et al. [5] on parabolic trough collectors, and the NRMSE is 0.140 and as can be seen in Figure 4, the current research has an acceptable agreement with the previous research.

In this research, the performance of a parabolic trough collector (Eurotrough ET100) and a linear Fresnel Reflector (LF-11) have been investigated and compared.

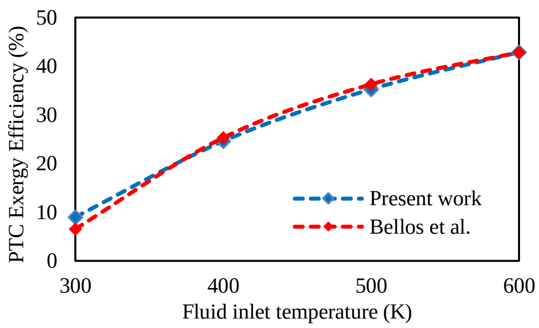

Figure 4. Validation of the present research with the work of Bellos et al. [5]

The physical properties of these collectors are given in Table 2. Also, the mass flow rate of the fluid is 2 kg/s and its type is Therminol VP1. Also, the fluid is assumed to enter the collector at ambient temperature without any pre-heating. According to the fluid characteristics and environmental conditions in Tables 2 and 3, the instantaneous peak thermal capacity of the parabolic trough collector is approximately 360 kW and the instantaneous thermal capacity of the linear Fresnel reflector is 246 kW.

The results show that the highest exergy destruction in both collectors is related to the absorber tube. It seems that the cause of this issue is the severe exergy destruction of the absorption of solar radiation on the surface of the absorber tube, which is caused by the large temperature difference between the sun and the surface of the absorber tube. After that, the exergy destruction in the reflector is the highest. This destruction is optical and its value has a direct dependence on the intercept factor of the reflector. Therefore, it can be seen that the exergy destruction in the reflector of the LFR is more than that of the PTC, and it accounts for a higher percentage of the total exergy destruction of the collector. Also, as the optical efficiency of the collector increases, exergy destruction in the working fluid and the glass cover also increases. The reason for this is an increase in the amount of incoming radiation to these components, with the improvement in the optical properties of the reflector such as intercept factor, reflection coefficient and etc. But in both cases, the ratio of exergy destruction of these components to the total exergy destruction of the collector does not change much (Table 4).

Table 2. Physical and geometric properties of the studied collectors [5, 7]

Parameter	Unit	PTC	LFR
k_r	$W.m^{-1}.K^{-1}$	52	52
k_g	$W.m^{-1}.K^{-1}$	0.8	0.8
L	m	99.5	65
W_a	m	5.77	7.5
D_i	m	0.066	0.066
D_o	m	0.070	0.070
D_{gi}	m	0.120	0.115
D_{go}	m	0.125	0.120
α_r	-	0.96	0.96
τ_g	-	0.97	0.97
ρ_{ref1}	-	0.94	0.95
ρ_{ref1}	-	-	0.95
γ	-	0.91	0.91
ε_r	-	0.095	0.095
ε_g	-	0.88	0.88

Table 3. Environmental conditions of the problem [8]

Parameter	Unit	Amount
G_B	$W.m^{-2}$	800
T_a	K	300
T_{sun}	K	5800
V_a	$m.s^{-1}$	5

In the following, the effect of change of solar radiation intensity and fluid mass flow rate on the exergy efficiency of parabolic trough and linear Fresnel collector will be studied. For this purpose, the investigated parameter is considered variable and other parameters are considered constant. For example, in the study of the effect of changing the solar radiation on the performance of the system, solar radiation is considered to be variable and other parameters are assumed to be constant. Also, the physical characteristics of the two collectors are considered to be the same in order to determine the role of the optical factors of the collectors. The length of both collectors is 100 meters and the width of each one is 6 meters. The reason for this assumption is that both collectors are subject to the same input so that the obtained results can be compared.

In the first part, the changes in the exergy efficiency values have been investigated in relation to the changes in the intensity of solar radiation in the range 200 to 1200 watts per square meter. As can be seen in Figure 5 as the radiation intensity increases, the exergy efficiency increases about 12% in LFR and 18% in PTC. Also, it seems that at low radiation intensity, the performance of the collectors does not differ much from the point of view of exergy. However, with an increase in intensity of solar radiation, the exergy destruction in the LFR increases more in compare with PTC, which is due to its lower optical efficiency. Also, the exergy efficiency of both collectors increases with an increase in the input radiation intensity, but this growth is not linear and its growth rate decreases with an increase in the radiation intensity.

Table 4. Exergy analysis results for the studied collectors

Exergy destruction	PTC		LFR	
	W	(%)	W	(%)
Reflector	61834	(17)	113590	(35)
Glass cover	11617	(3)	7801	(3)
Absorber tube	264607	(74)	184506	(57)
Fluid	20645	(6)	16223	(5)
Total	358701		322121	
Exergy efficiency	16.11 %		11.16 %	

In fact, with the increase of radiation intensity, the temperature of the surface of the absorber tube increases and decreases the exergy destruction due to absorption on the surface of the absorber tube. In such a situation, with an increase in solar radiation, the amount of input exergy increases more than the amount of exergy destruction of the whole system. In this way, with an increase in radiation intensity, the efficiency of the collector increases, but the slope of this increase in efficiency decreases with an increase in the radiation intensity. According to Figure 6 due to high amount of output exergy of PTC compared to LFR, variation of the cost of output exergy in PTC is negligible in compare with LFR. Also it can be concluded that operation of LFR is not economic under solar irradiation less than 600 W/m^2 due to its high price of output exergy. On the other hand, the parabolic trough collector produces more carbon dioxide compared to the linear Fresnel reflector due to the higher output useful exergy value.

In the second part, the changes in exergy efficiency and exergy destruction have been investigated in relation to the changes in mass flow in the range of 2 to 7 cubic meters per second. According to Figure 7, with the increase of fluid mass flow rate, total exergy destruction increases in both collectors and exergy efficiency decreases about 7.5% in LFR and 10% in PTC. But these changes do not occur linearly. In fact, by the increase in the fluid mass flow rate, the temperature of the collector decreases, and as a result, the exergy destruction of radiation absorption increases due to an increase in the temperature difference between the sun and the absorber tube. With the increase of mass flow, two basic things happen. First, the surface temperature of the absorber tube decreases, which increases the exergy destruction of heat absorption between the sun and the absorbent tube. And the other thing that happens is the increase of the heat transfer coefficient between the absorber tube and the fluid, which reduces the temperature difference between the inner surface of the tube and the fluid. So, the exergy destruction caused by heat exchange between the absorber tube and the working fluid is reduced. Of course, this decrease in destruction compared to the increase in

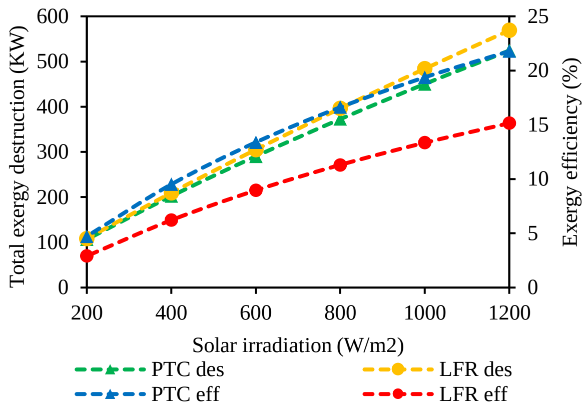

Figure 5. Changes in the amount of total exergy destruction and exergy efficiency in the investigated collectors with increasing intensity of solar irradiation

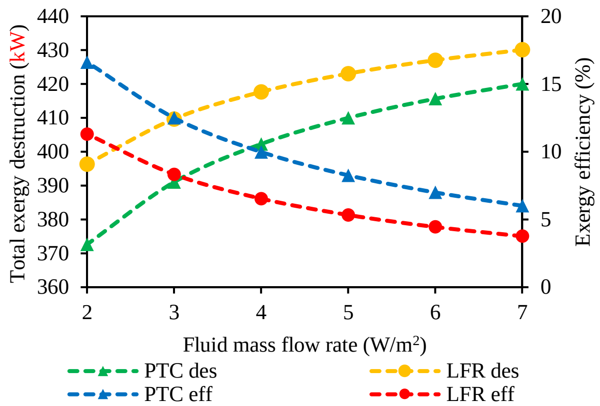

Figure 7. Changes in total exergy destruction rate and exergy efficiency in the investigated collectors with increasing the fluid mass flow rate

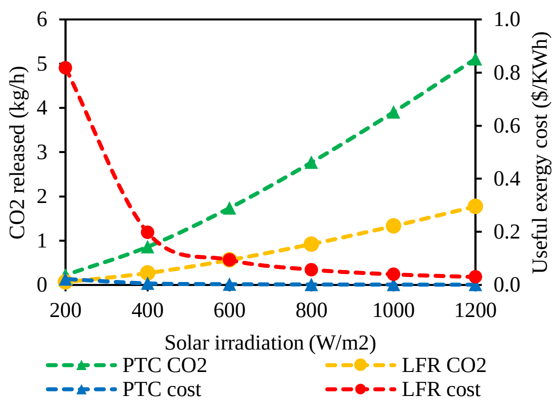

Figure 6. Changes in the rate of CO_2 release and cost of useful output exergy in the investigated collectors with increasing intensity of solar irradiation

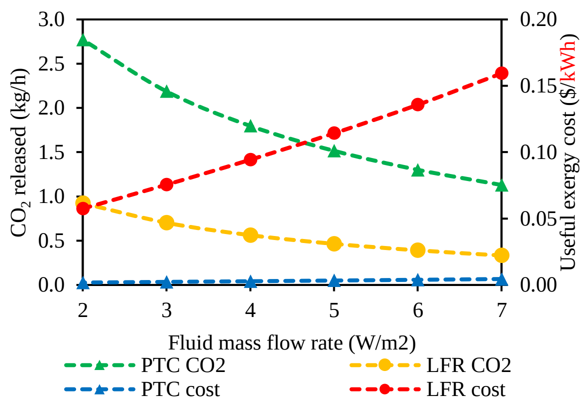

Figure 8. Changes in the rate of CO_2 release and cost of useful output exergy in the investigated collectors with increasing the fluid mass flow rate

the exergy destruction caused by the decrease in the temperature of the outer surface of the tube is very small and cannot disrupt the process of increasing the total exergy destruction, but it causes a decrease in the growth rate of the total exergy destruction with an increase in the fluid mass flow rate. On the other hand, the lower optical efficiency of the linear Fresnel reflector compared to the parabolic trough collector has caused its exergy destruction to be always higher than the parabolic trough collector. Figure 8 is similar to Figure 6 and shows that the cost of PTC output exergy is much lower than LFR and its value does not change much with the change of fluid flow rate, compared to LFR. Also, due to the large difference in the amount of exergy output in PTC compared to LFR, under the research conditions, the amount of carbon dioxide released in PTC is about 3 to 3.5 times that of LFR.

Finally, by examining Figures 5 to 8, it can be concluded that the exergy efficiency of a PTC is about 1.5 times that of LFR and the cost of the exergy output from the LFR is approximately 30 to 35 times that of the PTC. Therefore, the parabolic trough collector is completely preferable compared to the linear Fresnel reflector from exergy and economy point of view.

CONCLUSION

In this research, a parabolic trough collector and a linear Fresnel reflector were investigated and compared from the point of view of exergy, and the effects of solar radiation intensity and fluid mass flow rate on each were investigated. In the following, the results of this research will be briefly reviewed:

- The exergy efficiency in the parabolic trough collector is approximately 1.5 times that of the linear Fresnel reflector due to its higher optical efficiency.
- As the solar radiation intensity increases, the exergy efficiency of both collectors increases. On the other hand, by the increase of radiation intensity, the temperature of the collector increases, which causes a slight decrease in exergy destruction. Therefore, an increase in the total exergy destruction of the whole system with the increase in the intensity of the solar radiation is not linear, and with the increase in the intensity of the radiation, the slope of its increase decreases.
- The price of each kilowatt hour of exergy output of LFR is about 30 to 35 times that of PTC. So, PTC is much preferable to use compared to LFR.
- As the fluid mass flow rate increases, the surface temperature of the absorber tube decreases and as a result, the amount of exergy destruction in the collector increases. On the other hand, with the increase in mass flow rate, the convection heat transfer coefficient increases and the temperature difference between the tube and the fluid decreases. In this way, taking into account both of these factors, it is concluded that with the increase in fluid mass flow rate, the exergy destruction increases, but the its growth rate decreases with the flow rate increase.
- The rate of CO_2 release of PTC under equal conditions is about 3 to 3.5 times that of LFR due to its higher rate of output exergy.

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Persian Abstract

چکیده

استفاده از منابع انرژی تجدیدپذیر و مطالعه پیرامون آنها در سالیان اخیر رشد قابل توجهی داشته است. در این تحقیق دو کلکتور سهموی خطی و فرنل خطی، که کاربرد زیادی در حوزه انرژی خورشیدی دارند، از دیدگاه اگزرژی مورد بررسی قرار گرفته است. ابتدا معادلات تعادل انرژی برای اجزاء مختلف کلکتور، با استفاده از روش های عددی حل شده و توزیع دما در هر جزء کلکتور به دست آمد. سپس مقادیر تخریب اگزرژی در هر جزء سیستم محاسبه گردید. مقایسه نتایج بدست آمده در کار حاضر با نتایج پژوهش قبل مطابقت خوبی را نشان می دهد. نتایج نشان می دهند که بازده اگزرژی در کلکتور سهموی بیشتر از کلکتور فرنل خطی است. همچنین روند تغییرات بازده اگزرژی و تخریب اگزرژی کل کلکتور با افزایش شدت تابش خورشید و دبی جرمی سیال برای هر دو کلکتور مورد بررسی و مقایسه قرار گرفته است.