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The Exergy Optimization of a Flat-Plate Solar Collector using AL_2O_3-Water, CuO-Water and TiO_2-Water Nanofluids by Genetic Algorithm

E. Boustani[*]
MSc. Student

A.M. Lavasani[†]
Associate Professor

In this study, the exergy efficiency of a flat plate solar collector using Al_2O_3, TiO_2, CuO nanoparticles and pure water as base fluid is studied. Solar radiation is selected between 200 to 600 W/m^2. The method to determine optimum values of optimization variables has been developed by Genetic Algorithm Toolbox in MATLAB software. Results show by increasing solar radiation the optimized exergy efficiency is increased 3.72% for Al_2O_3 and TiO_2nanofluids and 3.6% for CuO nanofluid. According to optimum values of mass flow rate of fluid, 15.22% for Al_2O_3 and TiO_2 nanofluids and 4.35% for CuO nanofluid is decreased, also collector inlet temperature is decreased about 0.8% for all nanofluids. By increasing wind speed and ambient temperature for both cases, the exergy efficiency increased and decreased respectively. Using nanofluids decreased 0.4% overall loss coefficient of collector.

Keywords: Exergy, Nanofluid, Flat plate, Solar Collector, Genetic Algorithm

1 Introduction

The sun is a source of reversible energy. Solar collectors can collect solar energy and convert to heat. One of the types of solar collectors is flat plate solar collector. The flat plate solar collectors have low efficiency compare with other collector types [1] so optimization of flat plate solar collectors is important for reach to better efficiency.

According to the energy equations do not show all of the internal losses of a energy system, So using exergy analysis is a suitable method for analysis and optimization of an energy system such as flat plate solar collector. One of the effective methods for enhancing thermal conductivity is replacing the base fluid by nanofluids to increasing the solar collector efficiency.

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[*] MSc. Student, Department of Mechanical Engineering, Central Tehran Branch , Islamic Azad University, Tehran, Iran, esm.boustani.eng@iauctb.ac.ir

[†] Corresponding Author, Associate Professor, Department of Mechanical Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran, arashlavasani@iauctb.ac.ir

In recent years, some researchers have investigated the flat plate solar collectors in different conditions. Colangelo et al. [2] have studied the ability of nanofluids to be used in solar collectors. Luminosu and Fara [3] by exergy optimization have found the optimal operation of a Flat plate solar collector in a numerical work. Farahat et al. [4] have studied exergetic optimization of a Flat plate solar collector using pure water and determined the optimal efficiency and other parameters. Kalogirou [5] had derived a general correlation for exergy efficiency. Otanicaret al. [6] have numericallyevaluated the performance of low-temperature DASCbased on the work of Tyagi et al. [7].

The past researches have not shown a comparison between the effects of using different nanofluids using as working fluid in a flat plate solar collector on its exergy efficiency.

In present study, exergy optimization for reach to better efficiency of a Flat plate solar collector using nanofluid instead of pure water had studied and specifications and demand parameters are considered, see Table (1). The nanofluid contains Al_2O_3, TiO_2 and CuO nanoparticles in water as base fluid. In this study collector inlet fluid temperature, mass flow rate of fluid and nanoparticle volume concentration selected as optimization variables and also the optimization operation have done with Genetic Algorithm (GA) toolbox in MATLAB software.

The geometry of the flat plate solar collector have shown as Figure (1).

Table 1 Specifications and demand parameters

Collector parameters	Sym.	value
Type	-	Black paint header-riser flat plate
Glazing	N	One glass
Absorption area	A_p	1.51 m^2
Collector dimensions	$L_1 \times L_2 \times L_3$	200×94×9.5 cm
Wind speed	V_w	20 m/s
Tilt angle	β	45 degree, south
Ambient temperature	T_a	300 K
Sun temperature	T_s	4350 K
Optical efficiency	η_o	0.84
Emissivity of the absorber plate	ε_p	0.96
Plate thickness	δ_p	0.005 m
Thermal conductivity of the absorber plate	k_p	383 W/mK
Emissivity of the covers	ε_c	0.9
Glass thickness	δ_c	0.004
Thermal conductivity of the insulation	k_i	0.05 W/mK
Thickness of the back insulation	δ	0.07 m
Thickness of the sides insulation	δ_e	0.04 m
Inner diameter of tube	D_i	0.01 m
thickness of tube		0.0009 m
Number of riser tubes	n_r	7
Length of riser tubes	L_r	2 m
Center to center distance of tubes	w	0.143 m

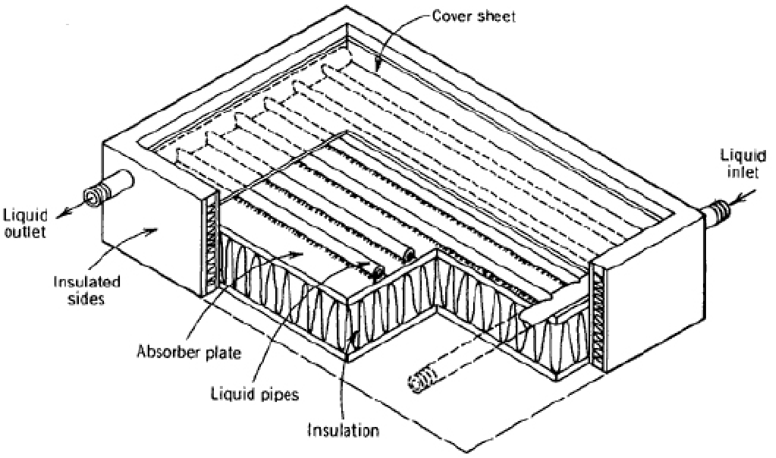

Figure 1 The geometry of a flat plate solar collector

2 Numerical Calculations

2.1. Nanofluid Properties

The properties of nanofluids including dynamic viscosity, thermal conductivity, heat capacity and density are obtained as follow correlations. Thermal conductivity (k) of the nanofluid can be calculated as the following Maxwell model [8].

$$k_{nf} = \frac{k_{np} + 2k_{bf} - 2\varphi(k_{bf} - k_{np})}{\frac{k_{np}}{k_{bf}} + 2 + \varphi(\frac{k_{bf} - k_{np}}{k_{bf}})} \tag{1}$$

Where φ is the volume concentration of nanoparticle and subscripts nf, np and bf are defined as nanofluid, nanoparticle and base-fluid, respectively.
Dynamic viscosity of nanofluid is calculated as the following Bachelor correlation [9].

$$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi + 6.5\varphi^2) \tag{2}$$

Density (ρ) and heat capacity (C_P) of nanofluid are determined by the following correlation respectively [10].

$$\rho_{nf} = \varphi\rho_{np} + (1-\varphi)\rho_{bf} \tag{3}$$

$$(\rho C_p)_{nf} = \varphi(\rho C_p)_{np} + (1-\varphi)(\rho C_p)_{bf} \tag{4}$$

The properties values for water and nanoparticles are given, see Table (2).

Table 2 Working fluids properties

Fluid	**C_P (J/kg.K)**	**ρ (kg/m^3)**	**k (W/m.K)**	**μ (kg/m.s)**
Water	4182	1000	0.6	-
Al_2O_3	773	3880	36	-
CuO	551	6000	33	-
TiO_2	692	4230	8.4	998×10^{-6}

2.2. Energy Analysis

The useful heat gain (Q_u) by the working fluid is calculated as following correlation [11].

$$Q_u = \dot{m}C_p\left(T_o - T_i\right) \tag{5}$$

Where, T_i, T_o, C_p and $\dot{m}$ are the fluid inlet temperature, outlet temperature, heat capacity and mass flow rate of the fluid, respectively. The Hottel–Whillier correlation for the useful heat gain (Q_u) of a flat plate solar collector is determined as following correlation [11].

$$Q_u = A_p F_R\left[S - U_l\left(T_i - T_a\right)\right] \tag{6}$$

Where, T_a is the ambient temperature and the heat removal factor (F_R) is defined as below [2].

$$F_R = \frac{\dot{m}C_p}{U_l A_p}\left[1 - \exp\left(\frac{-F'U_l A_p}{\dot{m}C_p}\right)\right] \tag{7}$$

In which F' is collector efficiency factor is calculated as following correlation [2].

$$F' = \frac{1}{\left(WU_l\left[\frac{1}{U_l\left[\left(W - D_o\right)F + D_o\right]} + \frac{\delta_a}{k_a D_o} + \frac{1}{\pi D_i h_f}\right]\right)} \tag{8}$$

The fin efficiency is calculated as below correlation [2].

$$F = \frac{\tanh\left[\left(\frac{U_l}{k_p\delta_p}\right)^{\frac{1}{2}}\frac{\left(W - D_o\right)}{2}\right]}{\left[\left(\frac{U_l}{k_p\delta_p}\right)^{\frac{1}{2}}\frac{\left(W - D_o\right)}{2}\right]} \tag{9}$$

Outlet fluid temperature from collector can be calculated as the following correlation.

$$T_o = T_a + \frac{S}{U_l} + (T_i - T_a - \frac{S}{U_l})\exp(\frac{-A_p U_l F'}{\dot{m}C_p}) \tag{10}$$

The overall heat loss coefficient is defined as following correlation [12].

$$U_l = U_t + U_b + U_e \tag{11}$$

$$U_b = \frac{k_i}{\delta_b} \tag{12}$$

$$U_e = \frac{(L_1 + L_2)L_3 k_i}{L_1 L_2 \delta_e} \tag{13}$$

$$U_t = \left[\frac{N}{\frac{C}{T_p}\left[\frac{T_p - T_a}{N + f}\right]^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{\left[\left(\varepsilon_p + 0.00591\ Nh_w\right)^{-1} + \frac{\left[2N + f - 1 + 0.133\ \varepsilon_p\right]}{\varepsilon_c} - N\right]} \tag{14}$$

That f, C and e are constant and equal to following correlations.

$$f = (1 + 089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N) \tag{15}$$

$$C = 520(1 - 0.00005\beta^2) \tag{16}$$

$$e = 0.43(1 - \frac{100}{T_p}) \tag{17}$$

That Ut is the heat loss coefficient from the top, Ub is the heat loss coefficient from the bottom and Ue is the heat loss coefficient from the edges of collector and N is the number of glass covers, hw is wind heat transfer coefficient, β is the collector tilt (in degrees), εe and εp are respectively the glass cover and absorber plate emissivity, and Tp is plate temperature is calculated as following correlation.

$$T_p = T_i + \frac{Q_u}{A_p F_R U_l}(1 - F_R) \tag{18}$$

hf in correlation (8) is the convective heat transfer coefficient of fluid flow inside tubes and can be estimated from the Nusselt number.

$$h_f = \frac{Nu \times k}{D_i} \tag{19}$$

Nusselt number for a water-based nanofluid flow inside one of the riser tubes can be calculated as the following correlations [10].

$$Nu_{nf} = 0.4328(1 + 11.285\varphi^{0.754} Pe^{0.218})\,\mathrm{Re}^{0.333}\,\mathrm{Pr}^{0.4} \tag{20}$$

$$Nu_{nf} = 0.0059(1 + 7.628\varphi^{0.6886} Pe^{0.001})\,\mathrm{Re}^{0.9238}\,\mathrm{Pr}^{0.4} \tag{21}$$

That correlation (20) is for laminar flow and correlation (21) is for turbulent flow.

2.3. Optical Analysis

The radiation absorbed flux by the absorber plate of solar collector is defined as below correlation [14].

$$S = (\tau\alpha)I_T \tag{22}$$

That the (τα) term is effective optical coefficient and for flat plate solar collector is equal to the optical efficiency [11].

2.4. Exergy Analysis

Exergy efficiency of a solar collector is equal to the ratio of the exergy increase with fluid flow and the initial radiation exergy [20].

The rate of inlet exergy with fluid flow is defined as following correlation [17-18].

$$\dot{E}_{i,f} = \dot{m}C_p\left(T_i - T_a - T_a \ln\left(\frac{T_i}{T_a}\right)\right) + \frac{\dot{m}\Delta P_i}{\rho} \tag{23}$$

and the rate of outlet exergy with fluid flow is defined as following correlation [14-15].

$$\dot{E}_o = \dot{m}C_p\left(T_o - T_a - T_a \ln\left(\frac{T_o}{T_a}\right)\right) + \frac{\dot{m}\Delta P_o}{\rho} \tag{24}$$

Also the rate of absorbed solar radiation exergy from source is calculated as below correlation [19-20].

$$\dot{E}_{i,Q} = \eta_o I_T A_p \left(1-\left(\frac{T_a}{T_s}\right)\right) \tag{25}$$

Finally, the exergy efficiency can be calculated as following correlation.

$$\eta_E = \frac{\dot{m}\left[C_p\left(T_o - T_i - T_a \ln T_o/T_i\right) - \frac{\Delta P}{\rho}\right]}{I_T A_p\left(1-T_a/T_s\right)} \tag{26}$$

That ΔP is flow pressure difference between entrance and exit of flat plate solar collector.

3 Numerical Calculations

In this study, optimization variables are flow rate, volume concentration of nanoparticle and inlet fluid temperature for nanofluids CuO, Al_2O_3, TiO_2 and pure water as working fluid in flat plate solar collector. the procedure to determine optimum values of this optimization variables for maximum exergy efficiency delivery has been developed by Genetic Algorithm (GA) Toolbox in MATLAB software under the below conditions.

$0 \le \dot{m} \le 0.2$ (Kg/s)
$300 \le T_i \le 420$ (K)
$0 \le \phi \le 1$ (%)

Before starting the optimization, The MATLAB software must be prepare, as below.

Population size: 150
Crossover: Constraint dependent
Mutation: Adaptive feasible
Generations: 150
Stall generation: 1000
Stall change: Average change
Function tolerance: 10^{-6}
Constraint tolerance: 10^{-3}

To validate theoretical exergy efficiency, η_{ex}, results compared to experimental study by Yousefi et al. [21] for pure water according to Table (3) and for Al_2O_3 nanofluid according to Table (4). Results show maximum error of method for pure water is 5.76% and for nanofluid is 4.21%, Therefore, The numerical method is acceptable.

Table 3 Comparison of theoretical and experimental work results of ref. [19] for pure water

I_T (w/m^2)	200	300	400	500	600
$\dot{m}$ (kg/s)	0.006	0.008	0.009	0.011	0.012
T_i (K)	329.28	342.24	354.48	366.18	377.41
η_{ex} (%)	4.54	6.32	7.92	9.39	10.75
$\eta_{ref[19]}$ (%)	4.8	6.7	8.16	9.52	10.59
error (%)	5.42	5.67	2.94	1.37	1.51

Table 4 Comparison of theoretical and experimental work results of ref. [19] for Al_2O_3 nanofluid

I_T (w/m^2)	200	300	400	500	600
$\dot{m}$ (kg/s)	0.005	0.007	0.008	0.009	0.010
T_i (K)	327.68	340.12	351.55	362.71	373.38
Φ (%)	0.123	0.149	0.157	0.168	0.177
η_{ex} (%)	4.72	6.56	8.22	9.73	11.13
$\eta_{ref[19]}$ (%)	4.9	6.8	8.3	9.64	10.68
error (%)	3.67	3.53	0.96	0.93	4.21

4 Result and Discussion

The optimum values of Exergy efficiency, flow rate, volume concentration of nanoparticle and inlet fluid temperature for nanofluids CuO, TiO_2 as working fluid in flat plate solar collector have been given as Table (5) and (6), respectively. Note that the optimum values for pure water and Al_2O_3 nanofluid have been given in Table (3) and (4), respectively.

The optimum value of solar collector Exergy efficiency in radiation intensities between 200 to 600 W/m^2 for Al_2O_3, TiO_2 and CuO nanofluids and also for pure water. By increasing of solar radiation intensity, the collector optimum exergy efficiency increases, that this increasing for nanofluids is more than the pure water, See Figure (2) and its caption.

The overall loss coefficient of the collector is one of the parameters affecting the exergy efficiency of collector which is highly dependent on environmental factors. The changing trend of this ratio by increasing the solar radiation intensity for nanofluids and water are investigated, see Figure (3). Using nanofluids decrease the overall loss ratio compared to pure water case.

The wind speed and ambient temperature affecting of exergy efficiency of the flat plate solar collector, respectively. By increasing the wind speed from zero to 35 m/s and for 400 W/m^2 solar radiation (case study), the exergy efficiency increased from 6.2 to 8.85%, 6.22 to 8.86%, 6.21 to 8.86% and 5.91 to 8.57% for CuO, Al_2O_3, TiO_2 and pure water, respectively. Also by increasing the ambient temperature from 280 to 305 K and for 400 W/m^2 solar radiation (case study), the exergy efficiency decreased from 8.52 to 8.13%, 8.54 to 8.14%, 8.53 to 8.13% and 8.23 to 7.84% for CuO, Al_2O_3, TiO_2 and pure water, respectively. See Figure (4) and Figure (5).

Table 5 Optimum values for CuO nanofluid

I_T (w/m^2)	200	300	400	500	600
$\dot{m}$ (kg/s)	0.006	0.008	0.009	0.01	0.011
T_i (K)	327.58	340.2	351.58	362.68	373.35
Φ (%)	0.097	0.13	0.136	0.137	0.156
η_{ex} (%)	4.71	6.55	8.21	9.72	11.12

Table 6 Optimum values for TiO_2 nanofluid

I_T (w/m^2)	200	300	400	500	600
$\dot{m}$ (kg/s)	0.005	0.007	0.008	0.009	0.1
T_i (K)	327.66	340.04	351.62	362.69	373.38
Φ (%)	0.116	0.136	0.15	0.16	0.169
η_{ex} (%)	4.72	6.56	8.22	9.73	11.13

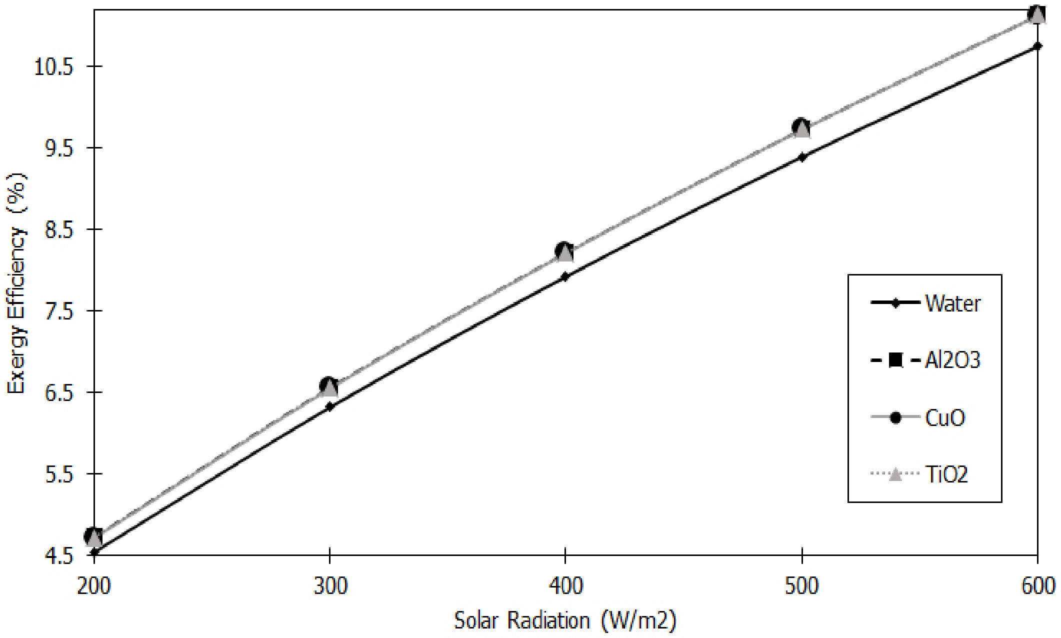

Figure 2 The effect of increasing of radiation intensity on the collector exergy efficiency

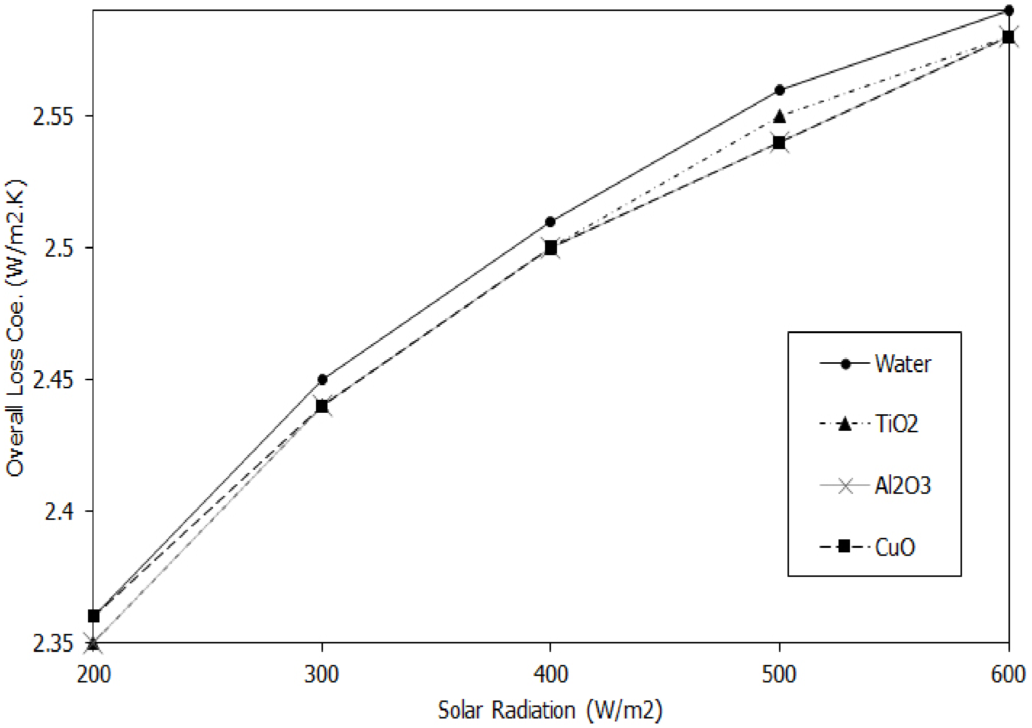

Figure 3 Overall loss coefficient changes into the solar radiation intensity

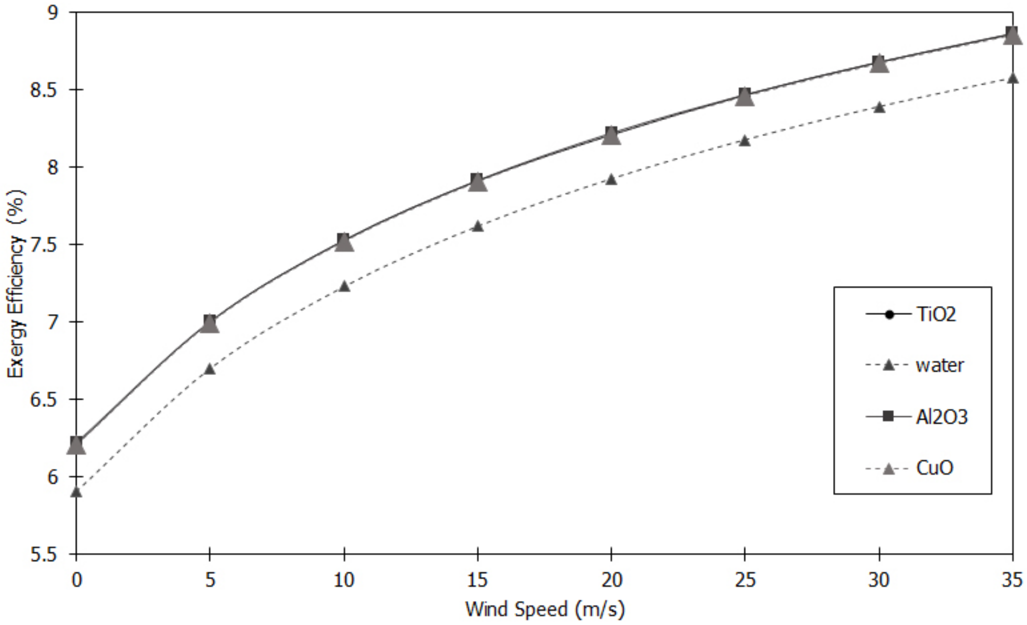

Figure 4 The effect of increasing of the wind speed on the collector exergy efficiency

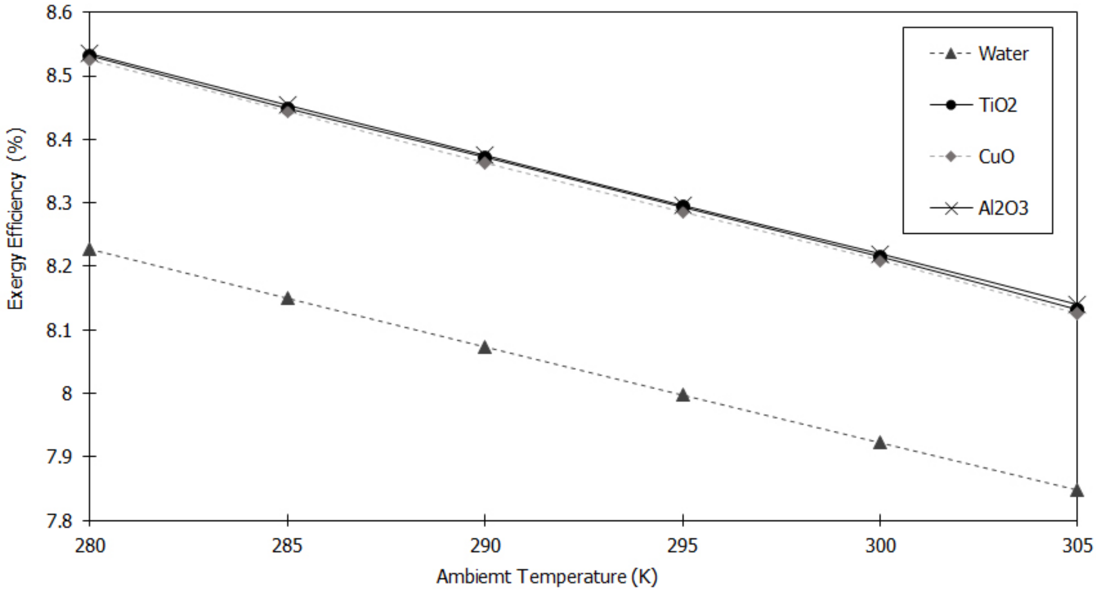

Figure 5 The effect of increasing of the ambient temperature on the collector exergy efficiency

According to properties of each nanofluid and also solar radiation, The Genetic algorithm gives special Fitness value versus the generations. For example, The following Chart is the Genetic algorithm output for Al_2O_3 nanofluid and solar radiation 300 W/m^2. According to Figure (5) the best fitness value and the mean fitness value are 0.0656128 (6.56128%) and 0.0656101 (6.56101%) respectively.

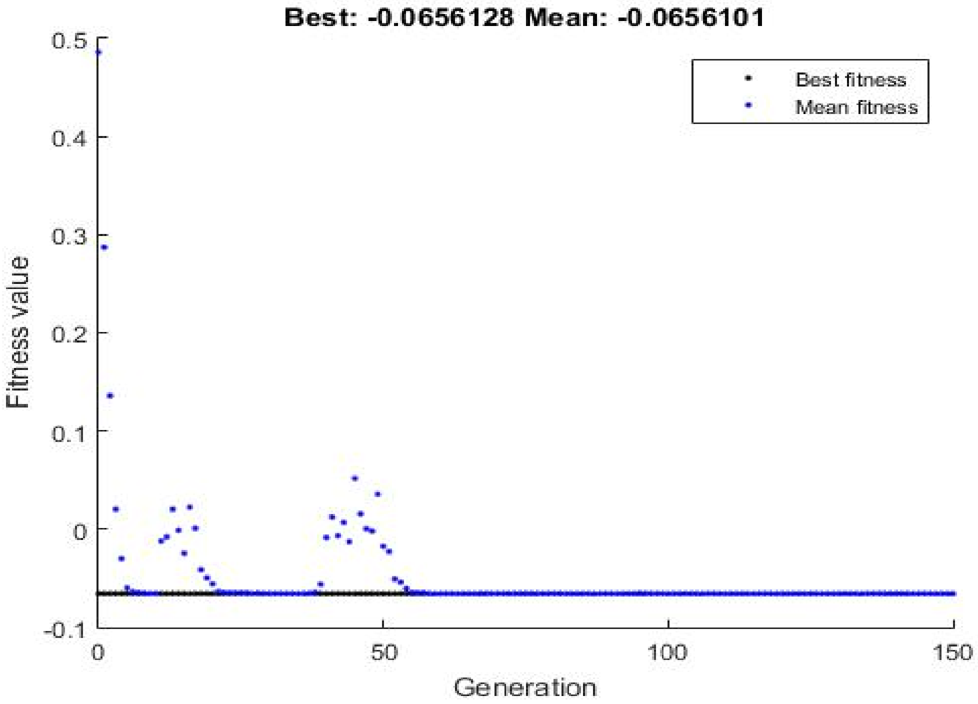

Figure 6 The fitness value for Al_2O_3 nanofluid and solar radiation 300 W/m^2

5 Conclusion

In this study, exergy efficiency optimization of a flat plate solar collector is investigated. Titanium dioxide, aluminum oxide and copper oxide nanofluids and pure water are used as working fluids. The range of solar radiation intensity is selected 200 to 600 W/m^2. Calculating variables to achieve maximum exergy efficiency (Optimization) is done with genetic algorithms (GA) by MATLAB software. The results show that

- Using of nanofluid instead of pure water as the working fluid in the collector, cause increasing in collector exergy efficiency between 3.58 to 3.7%. As well as aluminum oxide and titanium dioxide nanofluids have almost the same performance and have better performance compared to copper oxide nanofluid.
- All of nanofluids, aluminum oxide, copper oxide and titanium dioxide decreased collector inlet fluid temperature about 0.8% compared to the pure water.
- With increasing in solar radiation intensity from 200 to 600 W/m^2, the volume concentration of nanofluids has increased that been variable for aluminum oxide 0.123 to 0.177%, copper oxide 0.097 to 0.156% and titanium dioxide 0.116 to 0.169%.
- Using nanofluids instead of pure water reduces the mass flow rate of the fluid inside the collector and resulted in saving in system energy consumption. aluminum oxide and titanium dioxide nanofluids have reduced mass flow rate 15.22% and this value for copper oxide has been 4.35%.
- The wind speed increase affects on the exergy efficiency of collector directly. In other words, with an increase in wind speed from zero to 35 m/s, the collector exergy efficiency is increased about 4% in using both nanofluids and water as working fluid.

- Increase in the ambient temperature in glassy room cause reduction in collector exergy efficiency. Collector exergy efficiency has decreased almost 5.3 % for nanofluids and 4.6% for pure water with increasing ambient temperature from 280 to 305 K.
- Using nanofluids instead of water resulted in reduction of 0.4% overall loss coefficient. For radiation intensity 200 to 600 W/m^2, the overall loss coefficient for both fluid have increased about 2.36 to 2.59 for pure water and 2.35 to 2.58 for nanofluids.

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Nomenclature

A_c	Collector surface area (m^2)
C_p	Heat capacity (J/kg.K)
D_i	Inner diameter (m)
D_o	Outer diameter (m)
f	Friction factor
F	Standard fin efficiency
F'	Collector efficiency factor
F_R	Removal heat factor
g	Gravity acceleration (m/s^2)
I_T	Solar radiation on solar collector (W/m^2)
h_f	Heat transfer coefficient of fluid ($W/m^2.K$)
h_w	Heat transfer coefficient of wind ($W/m^2.K$)

k	Thermal conductivity (W/m.K)
K	Loss coefficient
k_p	Thermal conductivity of collector plate (W/m.K)
k_i	Insulation thermal conductivity (W/m.K)
L	Length (m)
$\dot{m}$	Mass flow rate (kg/s)
N	Number of glass covers
n_r	Number of risers
Nu	Nusselt number
Pr	Prandtl number
Pe	Peclet number
Q_u	Absorbed heat by plate (W)
U_l	Overall heat loss coefficient (W/m^2.K)
U_e	Heat loss coefficient of edges (W/m^2.K)
U_t	Thermal conductivity of collector plate (W/m^2.K)
U_b	Heat loss coefficient of bottom (W/m^2.K)
S	Received solar radiation to plate (W/m^2)
T_a	Ambient temperature (K)
T_i	Inlet fluid temperature of solar collector (K)
T_o	Outlet fluid temperature of solar collector (K)
T_p	Mean temperature of plate (K)
T_s	Sun temperature (K)
W	Tube spacing (m)

Greek Symbols

β	Tilt angle of solar collector (degree)
Δ	Difference
δ	Thickness (m)
ε	Emissivity
η	Efficiency (%)
$\tau\alpha$	Effective optical coefficient
φ	Volume fraction of nanoparticles in nanofluid (%)
ρ	Density (Kg/m^3)
μ	Viscosity (Kg/ms)

Subscripts

a	Ambient
bf	Base fluid
ex	Exergy
i	Inlet
nf	Nanofluid
np	Nanoparticle
o	Outlet
p	Absorber plate
s	Sun
u	Useful

چکیده

در مطالعه حاضر، بهینه‌سازی اکسرژی یک کلکتور خورشیدی صفحه تخت با سه نوع نانوسیال اکسید آلومینیوم، اکسید مس و تیتانیوم دی‌اکسید و همچنین آب خالص به عنوان سیال کاری بررسی شده است. شدت تابش خورشیدی از ۲۰۰ الی ۶۰۰ وات بر مترمربع انتخاب شده است. تأثیر پارامترهای مختلف مانند نرخ جریان جرمی، دمای سیال ورودی به کلکتور، غلظت حجمی نانوذرات در سیال پایه، شدت تابش خورشید، سرعت باد و دمای محیط داخل پوشش شیشه‌ای بر راندمان اکسرژی کلکتور، مورد مطالعه و بررسی قرار گرفته است. محاسبه متغیرهای بهینه‌سازی جهت دستیابی به بیشترین راندمان اکسرژی (بهینه‌سازی) با الگوریتم ژنتیک توسط نرم‌افزار متلب انجام شده است.

نتایج به‌دست آمده برای نانوسیالات و آب نشان می‌دهند با افزایش شدت تابش خورشید، مقدار غلظت حجمی نانوسیالات افزایش یافته و برای نانوسیال اکسید آلومینیوم ۰/۱۲۳ تا ۰/۱۷۷، اکسید مس ۰/۰۹۷ تا ۰/۱۵۶ و تیتانیوم دی‌اکسید ۰/۱۱۶ تا ۰/۱۶۹ درصد متغیر بوده است و همچنین راندمان اکسرژی کلکتور با نانوسیالات حداکثر ۳/۷ درصد افزایش می‌یابد. به‌علاوه با افزایش شدت تابش خورشیدی، نرخ جریان جرمی ۱۵/۲۲ درصد برای نانوسیالات اکسید آلومینیوم و تیتانیوم دی‌اکسید و ۴/۳۵ درصد برای نانوسیال اکسید مس و دمای سیال ورودی به کلکتور ۰/۸ درصد برای هر سه نانوسیال کاهش یافته است. افزایش سرعت باد و دمای محیط داخل پوشش شیشه‌ای به ترتیب باعث افزایش و کاهش راندمان اکسرژی کلکتور شده‌است.

با توجه به نتایج به‌دست آمده، از میان نانوسیالات مورد مطالعه، مشخص گردید استفاده از نانوسیالات اکسید آلومینیوم و تیتانیوم دی‌اکسید دارای عملکردی تقریباً مشابه و نسبت به نانوسیال اکسید مس، راندمان اکسرژی بیشتری را موجب می‌شوند. به علاوه استفاده از نانوسیال باعث کاهش ضریب کلی اتلاف کلکتور به میزان ۰/۴ درصد نسبت به آب خالص شده است.