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Research article

Solar driven Stirling engine - chemical heat pump - absorption refrigerator hybrid system as environmental friendly energy system

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A R T I C L E I N F O

Keywords:
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A B S T R A C T

Aim of this paper is to present an alternative environmental friendly energy system consisting of solar driven Stirling Engine, chemical heat pump and absorption refrigeration system. Solar energy is the main energy source and waste heat is rejected by the Stirling engine is utilized by the chemical heat pump and absorption refrigerator. This system presents an alternative environmental friendly energy system that produces electricity, cooling and heating same time. A parametric research is conducted considering power output, energy efficiency and exergy destruction rate. Results are obtained numerically and discussed. According to the results, system operates most efficiently at the high temperature ratio of the working fluids of the Stirling engine and high collector surface temperature. Maximum power output is 9.463 kW, maximum energy efficiency of the hybrid system is 0.337. Comparing these results with Stirling engine, maximum power output of the hybrid system increases 14% and energy efficiency increases 13% for the hybrid system.

1. Introduction

Trigeneration systems are provided power, heat and cooling form the one fuel source. This kind of systems have increased for last decades, because of the opportunity to use energy sources more efficient and -that's why-they are more environmental friendly. Environmental concerns such as global warming have gained attention. In addition to this, one of the most important problems is the exhausted fossil fuels. Using renewable energy more effectively may be a solution for overcoming energy and environmental problems. As it is known, solar energy is the most promising renewable energy because of its potential and another solution may be to be utilized low temperature heat sources more efficiently. Chemical heat pump (CHP) applications present possibility to be employed as the heat storage system or heating applications by using low temperature heat sources. They have big advantages comparing with vapor compression heat pumps, since they consume less electricity and provides relatively higher temperatures. Absorption refrigeration (AR) systems are the systems that are driven by thermal energy and this thermal energy may be produced by the renewable energy (solar, geothermal etc.) or waste heat. This make absorption refrigerators more attractive for the combined heat and power systems where waste heat rejected to the environment. It is possible to design a hybrid system including solar driven Stirling engine-CHP-AR to employ energy more effective. Stirling cycles and solar driven Stirling engines are subjected to a number of studies as an alternative use of the renewable energy sources. Some examples can be seen in refs. (Iskander and Musmar, 2013; Mohammad et al., 2013a, 2013b, 2014; Formosa and Despesse, 2010; Sayyaadi et al., 2014; Martaj et al., 2007; Markman et al., 1983; Wu et al., 1998; Sharma et al., 2011; Ahmadi et al., 2015a, 2015b, 2016a, 2016b; Lanzetta et al., 2018). In addition, researches about the CHP and using of the AR in the hybrid systems can be found in the literature (Yang and Zhang, 2015; Zhang et al., 2011; Karaca et al., 2002; Kim et al., 1992).

In this paper, solar driven Stirling engine-chemical heat pump-absorption refrigerator hybrid system is taken in to account as an environmental friendly system. In the literature, to the best of the authors' knowledge, there is no system like considered in this paper. Parameters are chosen as power output, energy efficiency and exergy destruction to determine best performance of the system Regarding these parameters, it is aimed that an alternative hybrid system is presented and tried to define the best operation conditions. Parametric investigations are carried out and results are obtained and discussed.

2. System description

Solar driven Stirling engine - CHP- AR hybrid system is presented as

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Nomenclature

ExD	exergy destruction rate (kW)
H	molar enthalpy change (Joule/mol)
I	solar flux intensity (W/m^2)
k	heat conductance (W/K)
K	heat transfer coefficient (W/m^2)
$\dot{m}$	molar mass flow rate (mol/s)
$\dot{Q}$	heat rate (kW)
P	power output (kW)
r	internal irreversibility index
T	temperature (K)
x	compression ratio
y	alcohol fraction

Abbreviations

AR	absorption regreigerator
CHP	chemical heat pump

Subscripts

A	Alcohol
ar	absorption refrigerator
ac	acetone
c	chemical heat pump
dr	dehydrogenation
h	hybrid
H	high
hr	hydrogenation
L	low
o	environment
P	product
s	Stirling
sc	solar collector
vap	vapor

Greek letters

α	regenerator effectiveness
Δ	temperature difference of the heat source and heat sink (K)
λ	adiabatic index
η	energy efficiency (%)
θ	temperature ratio
φ	coefficient of performance

an alternative trigeneration system which produces electricity, heat and cooling processes from the one source which is renewable. Considered system is shown in Fig. 1. Main fuel source is the solar energy. Rejected heat from the Stirling engine can be used in a CHP for heating processes and in a AR for the cooling processes. CHP is a promising alternative for using renewable energy, waste heat and low temperature heat sources. Absorption refrigerator systems are the of the most convenient refrigerators to use waste heat or renewable energy similar to chemical heat pumps in spite of their lower COP value.

In this paper, Stirling engine is chosen, because, they enable them to be integrated to renewable energy sources and they are external combustion engines. In addition, they can be used in the micro cogeneration applications that could be applied in wide range.

CHP system is an alternative way to utilize the low temperature heat source or waste heat; and thus, the renewable energy including solar and geothermal energy can be utilized. In contrast to conventional steam-compressed heat pumps, they do not involve mechanical compression generally. In this study, i-propanol-acetone-hydrogen chemical heat pump is chosen. They have the capacity to provide heat to the environment at 150°C-200 °C and the operation pressure is about 1 or 2 bars. The operational process of the CHP originates from the dehydrogenation of methanol, ethanol or n-butanol and hydrogenation of formaldehyde, acetaldehyde or butyraldehyde, respectively. In these systems, the dehydrogenation reaction takes place at low-temperature (70–100 °C) and requires thermal energy while the hydrogenation reaction is carried out at high-temperature (150–200 °C) as an exothermic reaction. The alcohol produced by the hydrogenation reaction of aldehyde or ketone and hydrogen is recycled for dehydrogenation reaction. Part of low-level thermal energy is upgraded to high-level energy; and the rest is removed by condenser at ambient temperature. No mechanical energy is necessary as a driving force (Karaca et al., 2002).

Absorption refrigerator systems are the most convenient cycles to use waste heat or renewable energy similar to chemical heat pumps. The rejected heat from the Stirling engine can be utilized in an absorption refrigerator. The electricity consumption at AR can be neglected, when they are compared with mechanical compression system. NH_3 or Li-Br solutions are the most common working fluids for absorption refrigerators. Heat is provided to generator where refrigerator is vaporized, which leave as high pressure and high temperature vapor. After that, refrigerator is sent to condenser, expansion valve and evaporator, respectively; and in these processes, cooling is taken into account. Finally, refrigerant is sent to the absorber; and is absorbed by the weak solution in the absorber.

Some assumptions for the system are listed as follows:

- All components are operating in steady state conditions.
- Rejected heat from the Stirling engine is assumed as the 80 °C.
- Heat released from the environment from the CHP is assumed as 150 °C.
- CHP is operated in 1 bar.
- Heat provided to CHP and AR is equal and it is half of removed heat from the Stirling engine.
- Power inputs to CHP and AR are neglected.

2.1. Analysis

Solar driven Stirling engine- CHP-AR hybrid system is analyzed for all components separately and for the hybrid system. From the first low of the thermodynamics power output of the Stirling engine one can be obtained by using eq. (1):

$$P_s = \dot{Q}_{H,s} - \dot{Q}_{L,s} \tag{1}$$

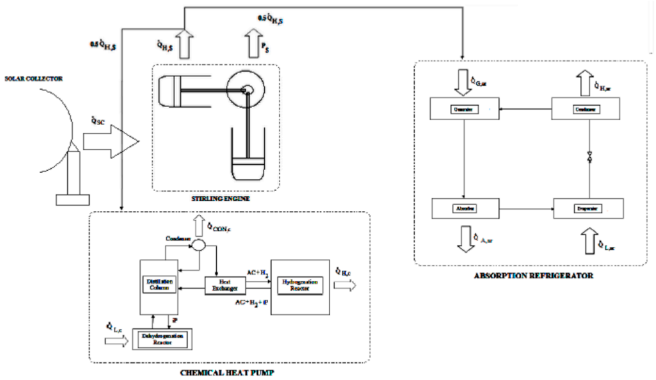

Fig. 1. Schematic of the hybrid system.

Energy efficiency of the Stirling engine can be written as ratio of the power output of the Stirling engine to heat supplied to the Stirling engine:

$$\eta_s = \frac{P_s}{\dot{Q}_{H,s}} \tag{2}$$

Power output and the efficiency including external and internal irreversibilities are described as eqs. (3) and (4) (Lanzetta et al., 2018):

$$P_s = \frac{(\theta - r_s)(\gamma - 1)\ln x + \ln([\theta - \alpha(\theta - 1)][\frac{1+\alpha(\theta-1)}{\theta}]^{r_s})}{(\theta - 1)[\frac{(\gamma-1)\ln x + (1-\alpha)(\theta-1)}{k_{L,s}(\Delta - T_{L,s} - (\theta-1))} + \frac{\theta \ln x(\gamma-1) + (1-\alpha)(\theta-1)}{k_{H,s}(T_{H,s}(\theta-1) - \theta\Delta)} + \frac{2}{k_{reg}\Delta}]} \tag{3}$$

$$\eta_s = \frac{(\theta - r_s)(\gamma - 1)\ln x + \ln([\theta - \alpha(\theta - 1)][\frac{1+\alpha(\theta-1)}{\theta}]^{r_s})}{\begin{gathered}\theta(\lambda - 1)\ln x + (\theta - 1)[(1 - \alpha) \\ + k_{l,s}(T_H - T_L)[\frac{(\gamma-1)\ln x + (1-\alpha)(\theta-1)}{k_{L,s}(\Delta - T_{L,s} - (\theta-1))} + \frac{\theta \ln x(\gamma-1) + (1-\alpha)(\theta-1)}{k_{H,s}(T_{H,s}(\theta-1) - \theta\Delta)} \\ + \frac{2}{k_{reg}\Delta}]]\end{gathered}} \tag{4}$$

where, $k_{H,s}$, $k_{L,s}$, $k_{l,s}$ are the heat conductance of the heat force, heat sink and heal leak, θ is the temperature ratio of the working fluid, r_s is the irreversibility parameter, α is the regenerator effectiveness, Δ is the temperature difference of the heat source and heat sink, λ is the adiabatic index, x is the compression ratiıo. One can yield heat supplied and heat rejection from the Stirling engine by using eqs. (1)–(4). Temperature of the heat source can be provided by using eq (5) that is efficiency of the solar collector where, ε is the emissivity, I is the solar flux intensity and σ is the Stephan-Boltzmann constant.

$$\eta_{sc} = \frac{\epsilon\sigma}{I}(T_{sc} - T_H) \tag{5}$$

Exergy destruction rate of the Stirling engine is defined as follows (SienıutyczMıchael and Von Spakovsky, 1998):

$$ExD_s = T_o\frac{\dot{Q}_{H,s}}{T_{L,s}}(1 - \eta_s - \frac{T_{L,s}}{T_{H,s}}) \tag{6}$$

Thermodynamic relations for the CHP should be written. Heat addition (W) to the CHP is written in eq. (7) (Karaca et al., 2002):

$$\dot{Q}_{L,c} = \dot{m}_{ac}\left(\Delta H_{dr} - \Delta H_{vap(AD/K)} - \Delta H_{vap(A)}\left(\frac{y_A}{1 - y_A}\right)\right) \tag{7}$$

where, is the molar flow rate of the acetone, ΔH_{dr} is the enthalpy change of the dehydrogenation reaction, $\Delta H_{vap(AD/K)}$ enthalpy change of vaporization of aldehyde or keton, $\Delta H_{vap(A)}$ enthalpy change of the alcohol y_A is the alcohol fraction in vapor phase. Heat rejection to the environment for heating process can be described in eq. (8) (Karaca et al., 2002):

$$\dot{Q}_{H,c} = -\dot{m}_{ac}\Delta H_{hr} \tag{8}$$

where, ΔH_{hr} is the enthalpy change of hydrogenation reaction. Hydrogenation and dehydrogenation equations are expressed in eqs. (9) and (10) (Karaca et al., 2002):

$$\begin{aligned}\Delta H_{dr} = {} & 82261.638 - 241.734T + 1.30314T^2 - 2.6713 \times 10^{-3}T^3 \\ & + 1.866941 \times 10^{-6}T^4\end{aligned} \tag{9}$$

$$\begin{aligned}\Delta H_{rh} = {} & -53139.911 - 1.011T - 4.0687 \times 10^{-2}T^2 + 6.7723 \times 10^{-5}T^3 \\ & - 3.015875 \times 10^{-8}T^4\end{aligned} \tag{10}$$

enthalpy change in the vaporization process is (Karaca et al., 2002):

$$\Delta H_{vap,2(AC/P)} = \Delta H_{vap,1(AC/P)}[\frac{(1 - \frac{T_2}{T_{cr}})}{(1 - \frac{T_1}{T_{cr}})}]^n \tag{11}$$

where, T_1 is the initial temperature, T_2 is the final temperature and T_{cr} is the critical temperature. $\Delta H_{vap,2(AC/P)}$ is the final enthalpy change of the vaporization process and $\Delta H_{vap,1(AC/P)}$ is the initial enthalpy change of the vaporization process From the first law of the thermodynamics, rejected heat from the condenser can be expressed as (Kim et al., 1992):

$$\dot{Q}_{L,c} - \dot{Q}_{H,c} = \dot{Q}_{CON,c} \tag{12}$$

mol flow rate of the acetone can be calculated by using eq. (13):

$$\dot{m}_{ac} = \frac{0.5\dot{Q}_{H,s}}{(\Delta H_{dr} - \Delta H_{vap(AD/K)} - \Delta H_{vap(A)}(\frac{y_A}{1 - y_A}))} \tag{13}$$

Exergy destruction rate of the CHP is (Kim et al., 1992):

$$ExD_c = T_o(\frac{\dot{Q}_{H,c}}{T_{H,c}} + \frac{\dot{Q}_{CON,c}}{T_{C,c}} + \frac{\dot{Q}_{L,c}}{T_{L,c}}) \tag{14}$$

COP of the CHP is:

$$\varphi_c = \frac{\dot{Q}_{H,c}}{\dot{Q}_{L,c}} \tag{15}$$

Equivalent power output of the CHP (W) is (Yang and Zhang, 2015; Zhang et al., 2011):

$$P_c = \dot{Q}_{H,c}(1 - \frac{T_o}{T_{H,c}}) \tag{16}$$

Equivalent efficiency of the CHP is (Yang and Zhang, 2015; Zhang et al., 2011):

$$\eta_c = \frac{P_c}{\dot{Q}_{H,c}} \tag{17}$$

Analysis of the absorption refrigerator is shown in eqs. (18)–(28). COP of the AR can be seen in eq. (18) (Zhang et al., 2011):

$$\begin{aligned}\varphi_{ar} = \frac{\dot{Q}_{L,ar}}{\dot{Q}_{H,ar}} = 0.5\Bigg(&\sqrt{\left[\left(1 + \frac{T - B^2T_o}{(1 + B)^2T} + \frac{T_o - T_{L,ar}}{C\dot{Q}_{H,ar}}\right)^2 - 4T_{L,ar}\left(\frac{1}{(1 + B)^2T} - \frac{T_o - T}{C\dot{Q}_{H,ar}T}\right)\right]} \\ & - \left(1 + \frac{T - B^2T_o}{(1 + B)^2T} + \frac{T_o - T}{C\dot{Q}_{H,ar}}\right)\Bigg)\end{aligned} \tag{18}$$

r_{ab} internal irreversibility parameter of the AR,b_1,b_2, B are shown in eqs. (19)–(22):

$$B = \frac{(\sqrt{b_2} - 1)}{(1 + \sqrt{b_1})} \tag{19}$$

$$b_1 = \frac{K_{H,ar}}{K_{CON,ar}} \tag{20}$$

$$b_2 = \frac{K_{H,ar}}{K_{L,ar}} \tag{21}$$

$$C = \frac{(1 + B)^2(1 + \sqrt{b_1})^2}{A_{ar}K_H} \tag{22}$$

where, $K_{H,ar}$ K_{CON} and $K_{L,ar}$ are heat transfer coefficient of the generator, the condenser and the evaporator respectively. From the first law of the thermodynamic, heat rejected from the condenser is (Yang and Zhang, 2015; Zhang et al., 2011):

$$\dot{Q}_{L,ar} + \dot{Q}_{G,ar} = \dot{Q}_{H,ar} + \dot{Q}_{A,ar} \tag{23}$$

If we define $\dot{Q}_{O,ar} = \dot{Q}_{H,ar} + \dot{Q}_{A,ar}$, Equivalent power, equivalent efficiency and exergy destruction rate of the AR is (Yang and Zhang, 2015; Zhang et al., 2011):

$$P_{ar} = \dot{Q}_{L,ar}\left(\frac{T_{L,ar}}{T_o} - 1\right) \tag{24}$$

$$\eta_{ab} = \frac{P_{ar}}{\dot{Q}_{H,ar}} \tag{25}$$

$$ExD_{ar} = T_o\left(\frac{\dot{Q}_{O,ar}}{T_o} - \frac{\dot{Q}_{H,ar}}{T} - \frac{\dot{Q}_{L,ar}}{T_{L,ar}}\right) \tag{26}$$

After this point, equivalent power and efficiency of the CHP and AR are called as power output and efficiency for the simplicity. Finally, power output, efficiency and exergy destruction ratio of the hybrid system are expressed in eqs. (27)–(29).

$$P_h = P_s + P_c + P_{ar} \tag{27}$$

$$ExD_h = ExD_s + ExD_c + ExD_{ar} \tag{28}$$

$$\eta_h = \frac{P_s + P_c + P_{ar}}{\dot{Q}_{H,s}} \tag*{(29}$$

3. Results and discussions

In this part, performance results of solar driven Stirling - CHP - AR hybrid system are considered. Performance parameters are chosen as power output, energy efficiency and exergy destruction rate. Variables θ, I and T_{sc} that are main parameters about performance of the hybrid system are chosen. When a variable is investigated, others are assumed as constant. Variations of the parameters are shown in Figs. 2–12 and *P-η-ExD* curve is drawn. Values used in calculations can be seen in Table 1.

One can see variations of the power outputs of the hybrid system, Stirling engine, CHP and AR according to θ in Fig. 2. According to results, optimum (maximum) points are obtained for the hybrid system, Stirling engine and AR except for the CHP. Optimum points are obtained at $\theta = 2.03$ for the hybrid system, $\theta = 2.09$ for the Stirling engine and $\theta = 1.34$ for the AR. Corresponding values are 9.463 kW

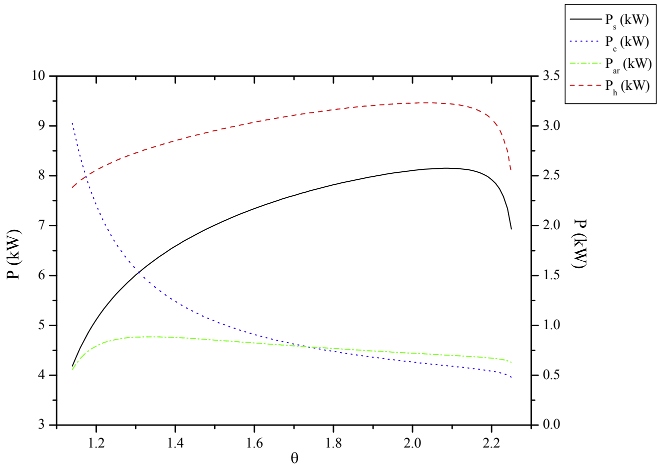

Fig. 2. Variations of the power outputs according to θ.

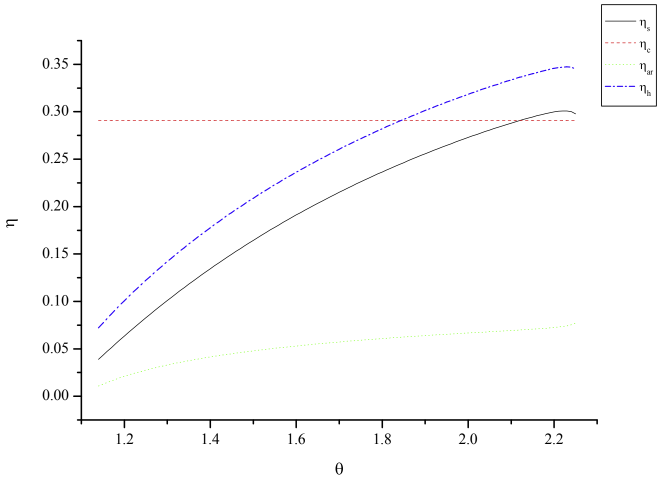

Fig. 3. Variations of the energy efficiencies according to θ.

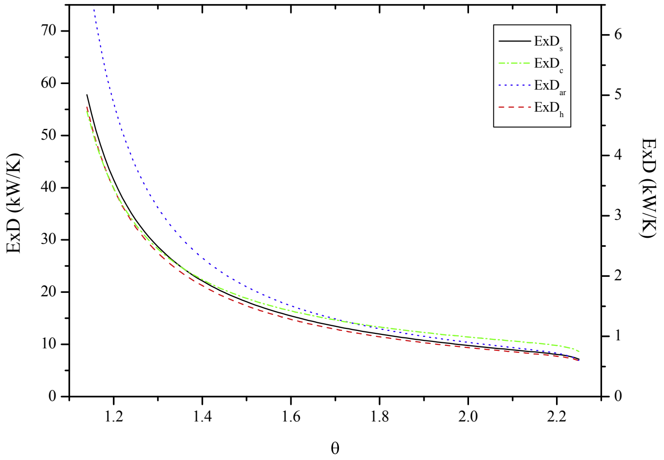

Fig. 4. Variations of the exergy destruction rates according to θ.

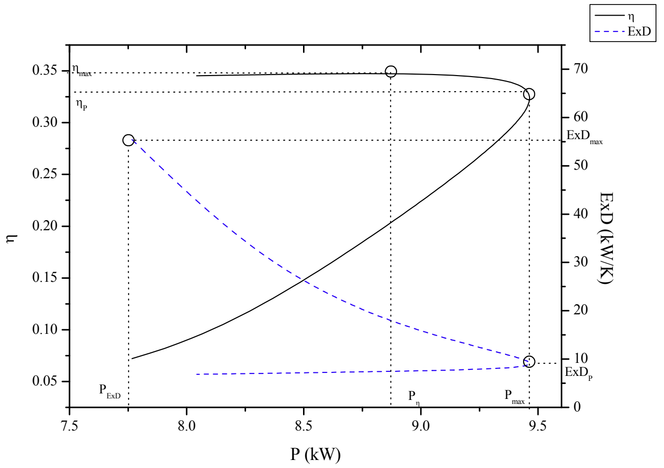

Fig. 5. P-η-ExD curve according to θ.

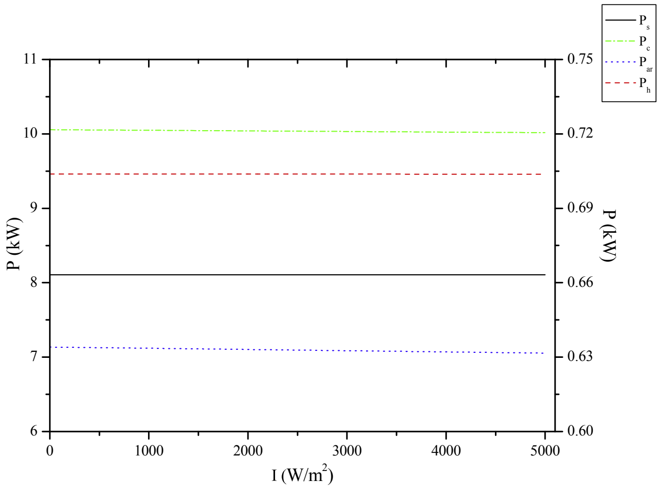

Fig. 6. Variations of the power outputs according to I.

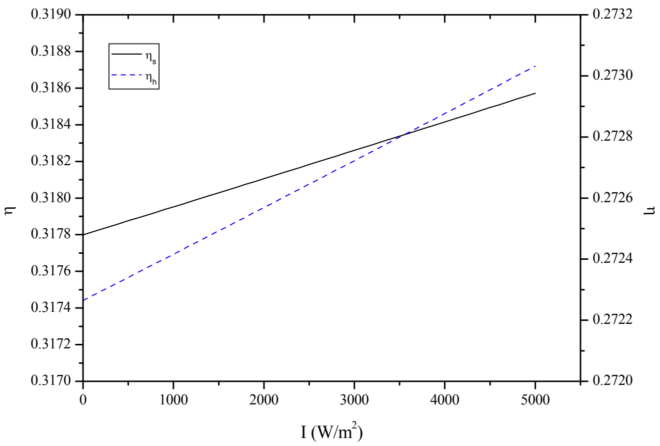

Fig. 7. Variations of the energy efficiencies according to I.

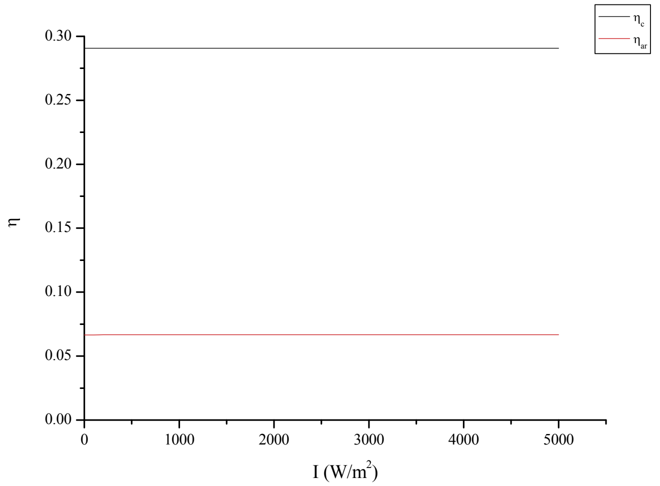

Fig. 8. Variations of the energy efficiencies according to I.

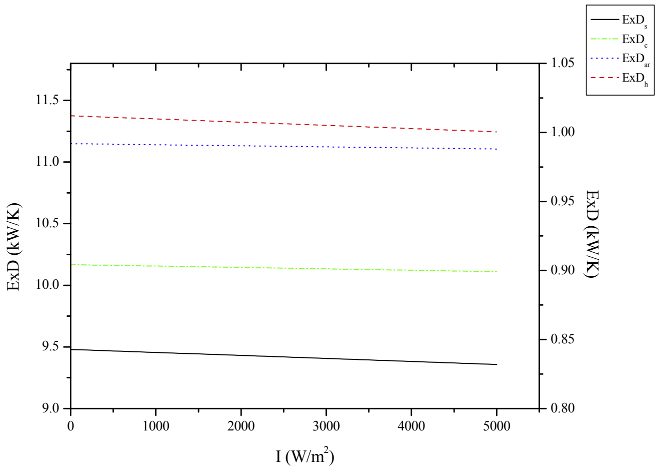

Fig. 9. Variations of the exergy destruction rates according to I.

8.152 kW and 0.885 kW respectively. For the hybrid system and Stirling engine, there is a dramatic fall after the optimum point. For the AR, variation of the power output is very fast until $\theta = 1.30$. For the CHP, power output changes fast about $\theta = 1.32$ after this value, its change is nearly linear and total decreasing according to θ is nearly 84%. As it is seen, CHP and AR get their higher power output at the lower θ values in contrast to Stirling engine and hybrid system.

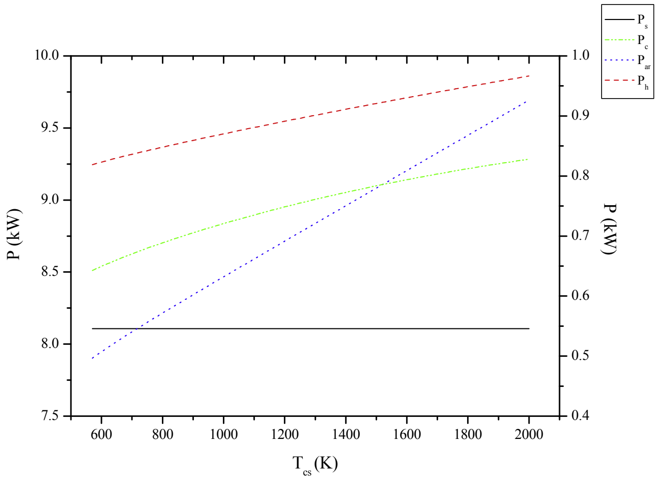

Fig. 10. Variations of the power output according to T_{sc}.

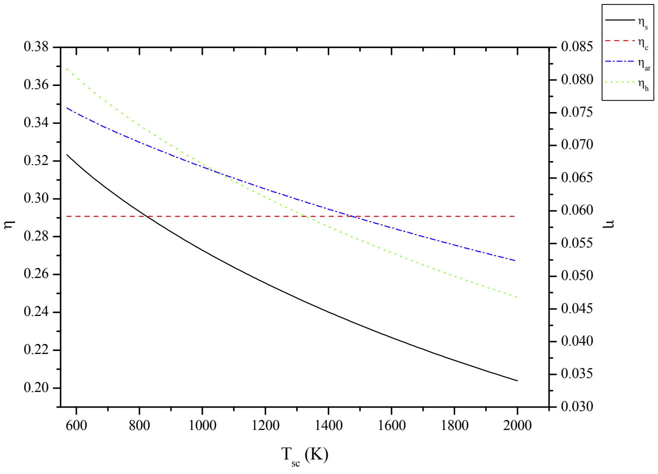

Fig. 11. Variations of the energy efficiencies according to T_{sc}.

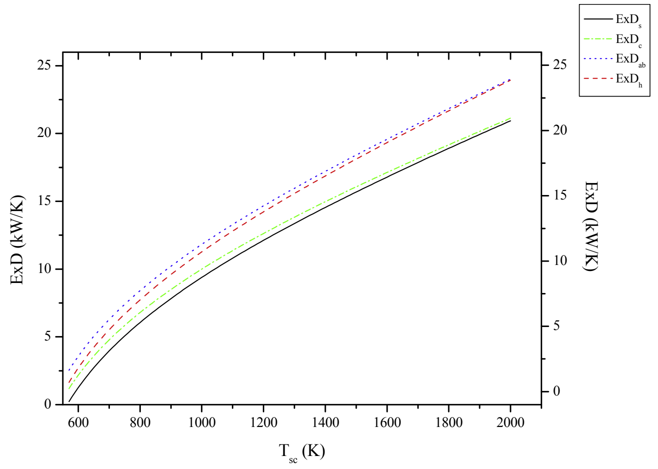

Fig. 12. Variations of the exergy destruction rates according to T_{sc}.

Energy efficiencies according to θ of the hybrid system, Stirling engine, CHP and AR can be seen in Fig. 3. Hybrid system and Stirling engine have maximum (optimum) points according to θ, efficiency of the AR increases with θ and efficiency of the CHP is the constant.

Table 1
Values used in calculations (Lanzetta et al., 2018; Yang and Zhang, 2015; Zhang et al., 2011; Karaca et al., 2002; Kim et al., 1992; SienıutyczMıchael and Von Spakovsky, 1998).

Parameter	Unit	Value
Δ	K	450
y	–	0.838
x	–	2
k_{reg}	W/K	100
$k_{l,s}$	W/K	10
$k_{L,s}$	W/K	10000
$k_{H,s}$	W/K	10000
$K_{H,ar}$	W/m^{2}K	1163
α	–	0.5
λ	–	1.4
r_s	–	1.05
ε	–	0.8
η_{sc}	–	0.3
b_1	–	1
b_2	–	1
r_{ab}	–	1.05
T_{sc}	K	1000
$T_{L,s}$	K	353.15
$T_{L,ar}$	K	278.15
T_o	K	300.15
$T_{CON,c}$	K	303.15

Hybrid system and Stirling engine reach their optimum points at the $\theta = 2.23$ and $\theta = 2.22$, corresponding values are 0.347 and 0.301 respectively. Efficiency of the CHP is equal 0.260 and there is no maximum efficiency for the AR and it increases with θ. As it can be seen, efficiencies have higher for the higher θ values of the hybrid system, Stirling engine and AR.

Exergy destruction rates according to θ are shown in Fig. 4. Exergy destruction rates of the all components decrease logarithmically with θ, these decreasing are really fast until $\theta = 1.40$ and after this point decreasing rate gets slow and change of the exergy destruction rates are nearly linear. The maximum exergy destruction rates for the hybrid system, Stirling engine, CHP and AR get their maximum at $\theta = 1.14$ and corresponding values are 66.723 kW/K, 57.813 kW/K, 3.152 kW/K and 5.758 kW/K respectively. One can say that θ value should be chosen high as possible as are reasonable in terms of exergy destruction rate.

According to these results, θ is chosen as $\theta_\eta < \theta < \theta_P$, where θ_η is the temperature ratio at the maximum energy efficiency of the hybrid system, and θ_P is the temperature ratio at the maximum power of the hybrid system.

P-η-ExD curve of the hybrid system according θ to is indicated in Fig. 5 where ExD_{max} is the maximum exergy destruction rate, ExD_P is the exergy destruction rate at the maximum power output, $P_{\max}$ is the maximum power output, P_η is the power output at the maximum efficiency, P_{ExD} is the power output at the maximum exergy destruction rate, $\eta_{\max}$ represents the maximum efficiency and η_P represents efficiency at the maximum power output. ExD_P is equal to 9.130 kW/K and it is 16% of the maximum exergy destruction rate, ExD_η is 7.358 kW/K and it is equal to 13% of the its maximum. P_η is 8.794 kW and it is equal to 92% of the its maximum value, P_{ExD} is equal to 7.767 kW and it is 82% of the its maximum value. η_P is equal to 0.323 and it is 93% of its maximum. Finally, η_{ExD} is 0.072 and it is 20% of the maximum efficiency. As it is seen, at the maximum power output, energy efficiency has higher value, while exergy destruction is lower. Same thing is correct for energy efficiency values, in this point power output is high, while exergy destruction rate is low. That's why, θ should be chosen as $\theta_\eta < \theta < \theta_P$.

In Figs. 6–9, variations of the power output, efficiency and exergy destruction rates are shown according to I. Nearly all variables are constant or it can be said that change of them can be neglected. Changes for the power outputs and efficiencies are less than 1% and changes of the exergy destruction rates are less than 2% between $I = 0$ W/m^2 and $I = 5000$ W/m^2.

In Figs. 10–12, variations of the power output, efficiency and exergy destruction rates are shown according to T_{sc}. For the power outputs, change of the power output of the Stirling engine is less than 0.1% and rising of the CHP, AR and hybrid system are 46%, 22% and 6% respectively. While investigating efficiencies, as one can see that efficiency change of the CHP is the constant, decreasing at the efficiency of the Stirling engine is 37%, decreasing at the efficiency of AR is 31% and decreasing at the efficiency of the hybrid system is 32%. Eventually, exergy destruction rates increase with T_{sc} and these increasing rate are nearly 100%.

4. Conclusions

In this research, a solar driven Strling engine-CHP-AR system is investigated. This system is proposed as an alternative trigeneration system that is environmental friendly. Analyses are performed in terms of power output, energy efficiency and exergy destruction rates, optimum values are defined if they are existed. Equivalent power output and efficiency are described for the CHP and AR. According to the results, system provides higher power outputs and efficiency and lower exergy destruction rates at higher temperature ratio. Temperature ratio of the working fluids should be chosen as $\theta_\eta < \theta < \theta_P$, in this range, decreasing at the maximum power output and the energy efficiency are not bigger than 4%. Effects of I and T_{sc} are considered and researched too and results show that effect of the T_{sc} is greater than the I. The higher T_{sc} causes the higher power output and energy efficiency, however, the higher exergy destruction rates too. Nevertheless, for the T_{sc}, increasing at the exergy destruction is only 5%, while increasing at the power output is 37% and increasing at the efficiency is 33%.

According to the results, One can say that higher temperature ratios of the working fluids and T_{sc} should be chosen for the more efficient hybrid system. For the future studies, it can be recommended that economical or thermo-economical evaluation of the hybrid system is researched and obtained results may be compared with the results presented in this paper.

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