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Conventional and advanced exergy analysis of a single flash geothermal cycle

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Abstract

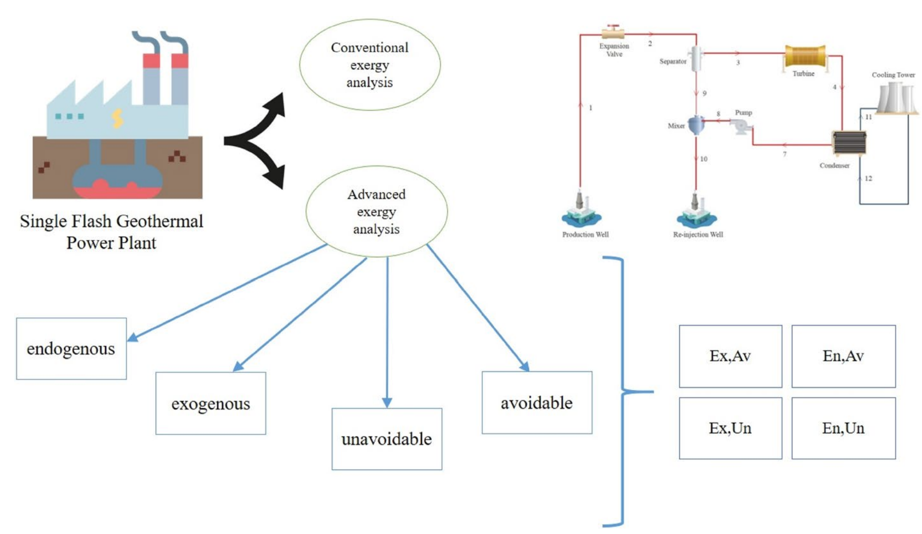
In this paper, the inefficiency of the studied energy conversion system is identified to reduce losses and improve performance. A conventional exergy analysis has limitations that it is not able to detect and this detection is done with advanced exergy analysis. The main role of advanced exergy analysis is to help engineers improve system design and performance by providing information. This provision of information is done by isolating the exergy destruction. Separation of exergy destruction into endogenous/exogenous and unavoidable/avoidable components presents a new development in the exergy analysis of energy conversion systems, which in this paper combines both concepts. This separation increases the accuracy of the exergy analysis and facilitates the improvement of a system. The method used in this paper for separation is the thermodynamic cycle method, which is based on determining the temperature levels for ideal and irreversible cycles.

Highlights

- The single flash geothermal cycle was subjected to advanced exergy analysis.
- Endogenous/exogenous and unavoidable/avoidable energy destruction were investigated.
- The results of the enhanced exergy analysis are distinct and more practical.

Keywords: Advanced exergy, Single flash geothermal cycle, Exergy destruction

Graphical Abstract



Introduction

Increasing annual energy needs and problems with fossil fuels have led to an increase in the study of renewable energy sources. One of these sources is geothermal energy (Fan et al. 2021; Aryanfar et al. 2022; Randow et al. 2022; Békési et al. 2022). The advantage of geothermal energy over other renewable energies is the continuity of the energy source (Appendix 2007; Pishkariahmadabad et al. 2021; Piipponen et al. 2022; Rink et al. 2022; Procesi et al. 2022). Using geothermal energy has several advantages over fossil fuel sources, but its main advantage is the absence of fuel supply costs. In addition, from the point of view of natural effects, the number of undesirable gases produced in these power plants is small (Wawerzinek et al. 2021; Dashti and Gholami Korzani 2021; Blanke et al. 2021). Other advantages of this type of power plant include the stability of the amount of energy extracted in all seasons of the year and the possibility of operating these power plants 24 h a day. From an economic point of view, the use of geothermal resources also reduces the dependence of the price of electricity produced on the price of fossil fuels (Hackstein and Madlener 2021; Siler et al. 2021; Park et al. 2021; Pleitavino et al. 2021). Many studies have been conducted in recent research on the analysis and optimization of the performance of geothermal power plant cycles. In a study, Jalili Nasrabady and Ryuichi (2012) investigated the efficiency of one-stage and two-stage instantaneous evaporation cycles for the Sabalan Geothermal Power Plant conditions (Iran). In a study, Yari (2010) analyzed the exergy of various geothermal cycles, including the simple binary cycle, the binary cycle with an internal heat exchanger, the recovery binary cycle, the single-stage instantaneous evaporation cycle, the two-stage instantaneous evaporation, and the evaporative binary composition. Zare (2015), in a study, analyzed and compared the exergo-economics of a simple binary cycle, a binary cycle with an internal heat exchanger and a recovery binary cycle for the three known operating fluids R152a, R245fa and n-Pentane.

New methods of saving energy and preventing energy wastage have led to the emergence of analytical methods based on the second law of thermodynamics, expressed in the form of the concept of exergy. General rules and methods of exergy analysis can be found in Kotas (1985) and Bejan (1996). Exergy analysis is an efficient tool for designing, optimizing and measuring the performance of energy systems. The advantage of exergy analysis is the ability to use all flow properties (temperature, pressure and composition). Exergy destruction is the value by which the irreversibility of the system is indicated (Fallah et al. 2022; Cao et al. 2022). Recognizing which components cost the most exergy destruction shows us the system's capabilities. Thermo-economics provides a powerful tool for optimizing and economically analyzing energy systems. Thermo-economics is a branch of thermodynamics in which the concept of exergy is combined with economic laws, and in fact, a more tangible indicator of irreversibility is found in the form of cost. Many studies have been conducted in exergy analysis (Sheikhi et al. 2014).

Advanced exergy analysis is a potential method to determine the actual improvement potential of the components of a system. In fact, in the advanced exergy analysis method, by dividing the destruction of exergy into endogenous/exogenous and avoidable/unavoidable parts as well as their combination, the path becomes smoother for detailed and more detailed studies of exergy of thermodynamic systems. Advanced exergy analysis is used to investigate the extent to which exergy destruction can be avoided or whether it is due to other components. The division of exergy destruction leads to a deeper understanding of its results and increases the accuracy of the analysis. Exergy destruction in one component is not only due to the performance of the component under study (endogenous exergy destruction) but also depends on the performance of other components (exogenous exergy destruction). In addition, consider whether exergy destruction of a component can be prevented (avoidable exergy destruction) or not (unavoidable exergy destruction). In summarizing the types of exergy analysis, it can be said that exergy and economic analysis of the system are examined from two different perspectives, and only in the discussion of an exergo-economic factor does economic analysis uses exergy results. In addition, advanced exergy analysis is, in fact, the next step of exergy analysis and further analysis of its results (Zheng et al. 2022; Sohrabi et al. 2022; Hamayun et al. 2022). Tsatsaronis first proposed the idea of advanced exergy analysis. Tsatsaronis and colleagues studied different cycles from the perspective of advanced exergy analysis. Tsatsaronis and Park (2002) stated the unavoidable exergy destruction and investment costs of compressors, turbines, heat exchangers and combustors for a cogeneration system. Kelly (2008) performed advanced exergy analysis in different ways for energy conversion systems and concluded that the method of thermodynamic cycles could be applied to all refrigeration systems. In addition, the engineering method is very accurate for studying thermal systems, but this method cannot determine the exergy destruction of dissipative components, such as a valve. Mersouk and Tsatsaronis (2008) investigated an absorption refrigeration cycle with advanced exergy. They introduced four advanced exergy analysis methods to determine exergy destruction's endogenous and exogenous components. Kelly et al. (2009), in another work, introduced four methods to calculate the endogenous part of exergy destruction. Their study showed that the thermodynamic cycle method gives the systems the most suitable results. The theoretical expander replaces the actual expansion process (quenching process) in the thermodynamic method. Fallah et al. (2016) investigated the Kalina cycle used in low-temperature geothermal resources, gas turbine cycle, solid oxide fuel cell, and solid oxide fuel cell with an anodic flow regenerator from the point of view of advanced exergy analysis and actual improvement potential.

Advanced exergy analysis provides more detailed information on the effect of system components on each other and the actual cycle improvement potential and provides some of the information designers require in designing and building cost-effective thermodynamic systems. Comparing the results of simultaneous analysis of thermodynamic systems from an economic point of view and advanced exergy provides a significant help in selecting more efficient system components, to minimize economic costs and exergy destruction. The single flash geothermal cycle has not been studied and compared simultaneously from the perspective of advanced exergy analysis. This information gap has been filled to provide designers with the information needed to select more efficient components at the lowest possible cost. In addition, in the advanced exergy analysis, the positive or negative effect of the inefficiency of each component on the inefficiency of the other components of the cycle has been investigated separately.

The main objectives of the present study are:

- Simulation and analysis of exergy and advanced exergy of single flash geothermal cycle
- Comparing the amount of exergy destruction of different cycle components
- Advanced exergy analysis of different components
- Providing a solution to reduce the amount of unavoidable exergy destruction of various components

After the introduction, the structure of the rest of the article is as follows:

The second part introduces the governing equations, including thermodynamic models and underlying equations, and the third part is the methodology and describes the cycle and its validation. The fourth part is the discussion and conclusion, and it shows mathematically and graphically the results of the proposed power plant's exergy and advanced exergy analysis. The last section shows the main results obtained in this paper.

Governing equations

Energy and exergy analysis

The law of conservation of mass and the first and second laws of thermodynamics are used to analyze the energy and exergy of thermodynamic systems. Considering the steady-state and regardless of kinetic energy and potential, the equations of mass balance, energy balance and exergy balance for the components of the cycle are as follows (Mohtaram et al. 2021a, b; Omidi et al. 2019; Chen et al. 2021):

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\dot{Q} + \sum \dot{\mathrm{m}}_{\mathrm{i}} h_i = \sum \dot{\mathrm{m}}_{\mathrm{e}} h_e + \dot{W} \tag{2}$$

$$\dot{E}_Q + \sum \dot{\mathrm{m}}_\mathrm{i} e_i = \sum \dot{\mathrm{m}}_\mathrm{e} e_e + \dot{W} + \dot{E}_D \tag{3}$$

In the above equations, $\sum \dot{\mathrm{m}}_\mathrm{i} h_i$ is the input enthalpy rate to the control volume, $\sum \dot{\mathrm{m}}_\mathrm{e} h_e$ is the output enthalpy rate to the control volume, $\sum \dot{\mathrm{m}}_\mathrm{i} e_i$ is the input exergy rate to the control volume, and $\sum \dot{\mathrm{m}}_\mathrm{e} e_e$ is the output exergy rate to the control volume. $\dot{E}_D$ is the rate of exergy destruction and $\dot{E}_Q$ is the rate of exergy associated with heat transfer, which is defined as follows (Haj Assad et al. 2021):

$$\dot{E}_Q = \sum (1 - \frac{T_0}{T}) \dot{Q} \tag{4}$$

Due to the absence of chemical changes and regardless of the ability to use kinetic energy and potential, current exergy includes only physical exergy:

$$e_{ph} = (h - T_0 s) - (h_0 - T_0 s_0) \tag{5}$$

The efficiency of the first law and the exergy efficiency are defined as follows:

$$\eta_\mathrm{th} = \frac{\dot{W}_\mathrm{net}}{Q_R} \tag{6}$$

$$\eta_\mathrm{ex} = \frac{\dot{W}_\mathrm{net}}{\dot{E}_{QR}} \tag{7}$$

The equation used to study the exergy for the k's component is as follows:

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \tag{8}$$

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{9}$$

In these equations $\dot{E}_{D,k}$, $\dot{E}_{F,k}$ and $\dot{E}_{P,k}$ are the exergy destruction rate, fuel exergy rate and product exergy rate are k's components, respectively.

Advanced exergy analysis

Advanced exergy analysis as a new concept in the exergy analysis of thermodynamic cycles states that the exergy destruction in a component is not only due to the irreversibility of the component itself but also due to the irreversible effect of other components of the cycle on the component.

In advanced exergy analysis, the rate of exergy destruction of component k is divided into endogenous and exogenous (Echeeri and Maalmi 2022; Sohrabi and Behbahaninia 2022):

$$\dot{E}_{D,k} = \dot{E}_{D,k}^\mathrm{EN} + \dot{E}_{D,k}^\mathrm{EX} \tag{10}$$

$\dot{E}_{D,k}^{EN}$ is part of the exergy destruction of the k's component due to the internal irreversibility of the component itself, and $\dot{E}_{D,k}^\mathrm{EX}$ is the part of the exergy destruction that results from the irreversible effect of the other components of the cycle on the performance of the *k*'s component. The exogenous exergy destruction of the *k* component due to the irreversible effect of the (*n*-1) component of the n-components cycle can be examined in more detail.

Also, by dividing the exergy destruction into two parts, avoidable and unavoidable, we can have a better understanding of the potential to improve the efficiency of cycle components (Sherwani 2022; Hashemian et al. 2022):

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{\mathrm{AV}} + \dot{E}_{D,k}^{\mathrm{UN}} \tag{11}$$

Unavoidable exergy destruction ($\dot{E}_{D,k}^{\mathrm{UN}}$) is a part of exergy destruction that cannot be reduced due to technical limitations, and avoidable exergy destruction ($\dot{E}_{D,k}^{\mathrm{AV}}$) is a part that can be reduced by upgrading and improving cycle components. Experimental destruction is achieved when the components of the cycle operate at their real unavoidable exergetic efficiency ($\varepsilon_{k}^{\mathrm{UN}}$). It should be noted that the unavoidable exergetic efficiency is the maximum efficiency that can be achieved by considering the industrial constraints (Xie et al. 2022; Boodaghia et al. 2014).

According to the above, the destruction of avoidable and unavoidable exergy can be divided into the following two parts:

$$\dot{E}_{D,k}^{\mathrm{AV}} = \dot{E}_{D,k}^{\mathrm{EX,AV}} + \dot{E}_{D,k}^{\mathrm{EN,AV}} \tag{12}$$

$$\dot{E}_{D,k}^{\mathrm{UN}} = \dot{E}_{D,k}^{\mathrm{EX,UN}} + \dot{E}_{D,k}^{\mathrm{EN,UN}} \tag{13}$$

We also have the division of endogenous and exogenous exergy into two parts, avoidable and unavoidable:

$$\dot{E}_{D,k}^{EN} = \dot{E}_{D,k}^{\mathrm{EN,AV}} + \dot{E}_{D,k}^{\mathrm{EN,UN}} \tag{14}$$

$$\dot{E}_{D,k}^{\mathrm{EX}} = \dot{E}_{D,k}^{\mathrm{EX,AV}} + \dot{E}_{D,k}^{\mathrm{EX,UN}} \tag{15}$$

In the above equations, $\dot{E}_{D,k}^{\mathrm{EN,UN}}$ refers to the destruction of the internal exergy of the k's component under unavoidable conditions, which is irreversible, and $\dot{E}_{D,k}^{\mathrm{EN,AV}}$ refers to the destruction of the internal exergy of the *k*'s component, which decreases as it improves. In addition, the destruction of exogenous exergy is the part of the exergy that is reduced by improving the structure of other components of the cycle, and the exorcism is unavoidable, which is irreversible due to technical limitations.

Various methods have been proposed in advanced exergy analysis, including the thermodynamic cycle method, the engineering method, the exergy balance method, the equivalent component method, and the structural theory method. In the present work, the method of thermodynamic cycles has been used due to its high accuracy and compatibility. It should be noted that in the cycle analysis in ideal and unavoidable conditions, the net power of the whole system is equal to the net power of the whole system in real conditions (Kelly 2008).

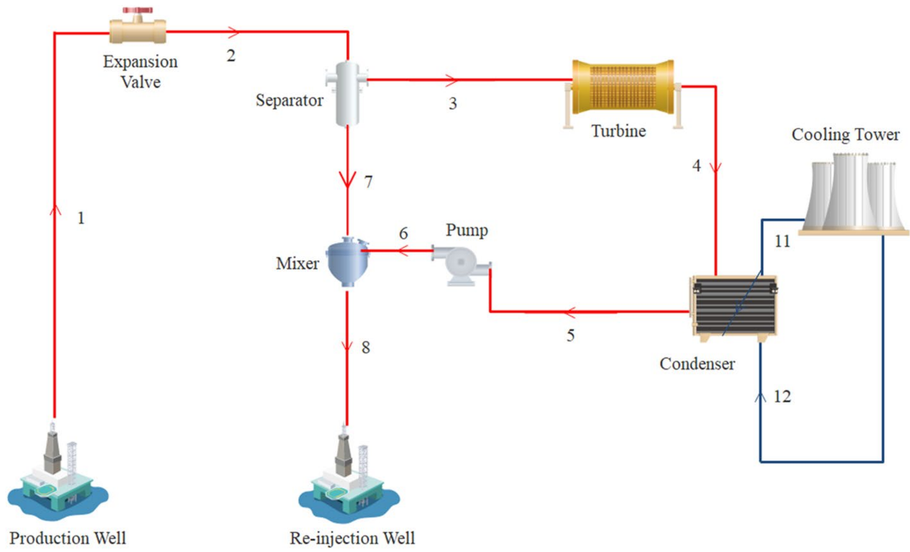


Fig. 1 Single flash geothermal cycle diagram

Table 1 Conventional exergy balance equations (Sun and Liu 2020)

Component	Exergy of fuel (or driving input) ($\dot{E}_{F,k}$)	Exergy of the product (or desired value) ($\dot{E}_{P,k}$)	Exergy destruction (or internal exergy loss) ($\dot{E}_{D,k}$)
Expansion Valve	$\dot{E}_{F,EV} = \dot{m}_1 e_1$	$\dot{E}_{P,EV} = \dot{m}_1 e_2$	$\dot{E}_{D,EV} = \dot{E}_{F,EV} - \dot{E}_{P,EV}$
Steam Turbine	$\dot{E}_{F,T} = \dot{m}_3(e_3 - e_4)$	$\dot{E}_{P,T} = \dot{W}_T$	$\dot{E}_{D,T} = \dot{E}_{F,T} - \dot{E}_{P,T}$
Condenser	$\dot{E}_{F,Cd} = \dot{m}_3(e_4 - e_5)$	$\dot{E}_{P,Cd} = \dot{m}_3(e_{11} - e_{12})$	$\dot{E}_{D,Cd} = \dot{E}_{F,Cd} - \dot{E}_{P,Cd}$
Pump	$\dot{E}_{F,P} = \dot{W}_P$	$\dot{E}_{F,P} = \dot{m}_7(e_8 - e_7)$	$\dot{E}_{D,P} = \dot{E}_{F,P} - \dot{E}_{P,P}$
Mixer	–	–	$\dot{E}_{D,Mix} = \dot{E}_{F,Mix} - \dot{E}_{P,Mix}$
Overall system	$\dot{E}_{F,tot} = \dot{W}_P$	$\dot{E}_{P,tot} = \dot{W}_T$	$\dot{E}_{D,tot} = \sum \dot{E}_{D,k}$

Methodology

Cycle description

Figure 1 shows a schematic diagram of a single flash geothermal power plant, which includes an expansion valve, separator, steam turbine, condenser, and pump. The geofluid (clean water) flows as a saturated liquid from the production well (state 1) to an expansion valve when its pressure and temperature drop, causing a two-phase flow. The two-phase flow (state 2) passes through an adiabatic separator, which separates the vapor (state 5) and sends it to the steam turbine. The residual liquid in the separator (state 7) is either injected back into the system or utilized as a waste heat source in low-temperature applications. In the turbine, the steam is expanded to state 4, two-phase, and then condensed to state 5 in the condenser. At stage 8, the flow leaving the condenser and separator is mixed before being used in additional applications. The following subsections present the applied equations for modeling this arrangement.

Table 2 Current study's design parameters

Parameter	Definition	Value
T_0	Ambient Temperature	25 °C
P_0	Ambient Pressure	100 kPa
T_1	Geothermal fluid inlet temperature	300 °C
$\dot{m}_1$	Geothermal fluid mass flowrate	50 kg/s
P_1	Geothermal fluid pressure	Saturated
P_2	Separator pressure	500 kPa
P_5	Steam turbine outlet pressure	20 kPa
η_T	Turbine isentropic efficiency	80%
η_p	Pump isentropic efficiency	80%
ΔT_{PP}	Heat Exchanger Pinch Point	12 °C

Table 3 Assumptions intended for real, ideal and unavoidable system conditions (Fallah et al. 2016; Gökgedik et al. 2016)

Component	Parameter	Real	Ideal	Unavoidable
Turbine	Isentropic efficiency	0.8	1	0.95
Pump	Isentropic efficiency	0.8	1	0.95
Throttling valve	–	Isenthalpic	Isentropic	Isenthalpic
Condenser	Pinch Point	$\Delta T_{min} = 12$	$\Delta T_{min} = 0$	$\Delta T_{min} = 3$

Table 4 Comparison of current simulation results with Assad et al. results (Assad et al. 2021)

State	Fluid	T (Kelvin)		P (MPa)		H (KJ/kg)	
		Current	Assad et al	Current	Assad et al	Current	Assad et al
1	Geo-fluid	573.2	573.2	8.584	8.584	1344	1344
2	Geo-fluid	448.2	448.2	0.8918	0.8918	1344	1344
3	Geo-fluid	448.2	448.2	0.8918	0.8918	2773	2773
4	Geo-fluid	323.1	323.1	0.01234	0.01234	2253	2253
5	Geo-fluid	323.2	323.1	0.01234	0.01234	209.3	209.3
6	Geo-fluid	323.2	323.3	0.8918	1.5	210.4	211.2
7	Geo-fluid	448.2	448.2	0.8918	0.8918	741.2	741.2
8	Geo-fluid	411.9	139	0.3483	0.352	583.7	584

The simulations are modeled using EES[1] software. The hypotheses used in the simulation are as follows:

- All components work in stable conditions.
- Changes in kinetic energy and potential are ignored.
- Heat transfer to the environment takes place only in the condenser.
- Turbines and compressors have isentropic efficiency.
- The lowest temperature difference is taken in the condenser 12 degrees Celsius.

[1] Engineering equation solver.

Table 5 Single flash geothermal cycle's thermodynamic data

State	T (K)	P (MPa)	H (KJ/kg)	S (KJ/kg.K)	$\dot{m}(\frac{kg}{s})$	x	Exergy (KW)
1	573.2	8.584	1344	3.253	50	0	18,931
2	448.2	0.8918	1344	3.436	50	0.2967	16,205
3	448.2	0.8918	2773	6.625	14.83	1	11,903
4	323.1	0.01234	2253	7.028	14.83	0.858	2405
5	323.2	0.01234	209.3	0.7037	14.83	0	60.28
6	323.2	0.8918	210.4	0.7044	14.83	–	73.74
7	448.2	0.8918	741.2	2.091	35.17	0	4302
8	411.9	0.3483	583.8	1.726	50	–	3684

Table 6 Results of advanced exergy analysis of various system components

Component	Exergy destruction	Endogenous	Exogenous	Avoidable	Unavoidable
Expansion Valve	2726	3008	− 282	− 210	2936
Steam Turbine	1780	1768	12	1283.4	496.6
Condenser	0	0	0	0	0
Pump	3.047	2.432	0.615	2.4376	0.6094
Mixer	691.8	728.2	− 36.4	− 84.8	776.6

The input data for the simulation for the single flash cycle under actual operating conditions are also given in Tables 1, 2.

The prevailing assumptions in the analysis of single flash geothermal cycle under real, ideal and inevitable conditions are given in Tables 2, 3. In addition to the assumptions mentioned in the table above, it should be noted that in the cycle analysis in ideal and unavoidable conditions, the net power of the whole system is equal to the net power of the whole system in real conditions.

Validation

The thermodynamic model of the single flash geothermal cycle is compared and validated with the results published by MEH Assad et al. And is shown in Table 4. Using the primary data of Assad et al.'s article, the single flash geothermal system is modeled to perform the validation process in the EES programming environment. Losses in pipes are ignored, and processes are assumed to be adiabatic. According to the table below, it is quite clear that the results of the thermodynamic model of the present work have a very good agreement with the results in the mentioned reference.

According to the assumptions of the problem, which include the absence of friction and losses in the pipes and isentropic processes, the pressure at points 7 and 8 should be equal according to the principles of thermodynamics. It is felt that in the article of Assad et al., this point was neglected, and as a result, they increased the value of 1.5 MPa for the pressure of point 7, which is wrong. For this reason, this mistake has been corrected in this modeling, and the value of 0.8918 has been obtained for both points; this argument justifies the difference between these two values (Table 5).

Table 7 Separation of endogenous and exogenous exergy degradation cycle of the cycle into avoidable and unavoidable

Component	Exergy destruction	En-Un(KW)	En-Av(KW)	Ex-Un(KW)	Ex-Av(KW)
Expansion Valve	2726	2726	282	210	−492
Steam Turbine	1780	1986	−218	−1489.4	1501.4
Condenser	0	0	0	0	0
Pump	3.047	2.887	−0.455	−2.2776	2.8926
Mixer	691.8	776.6	−48.4	0	−36.4

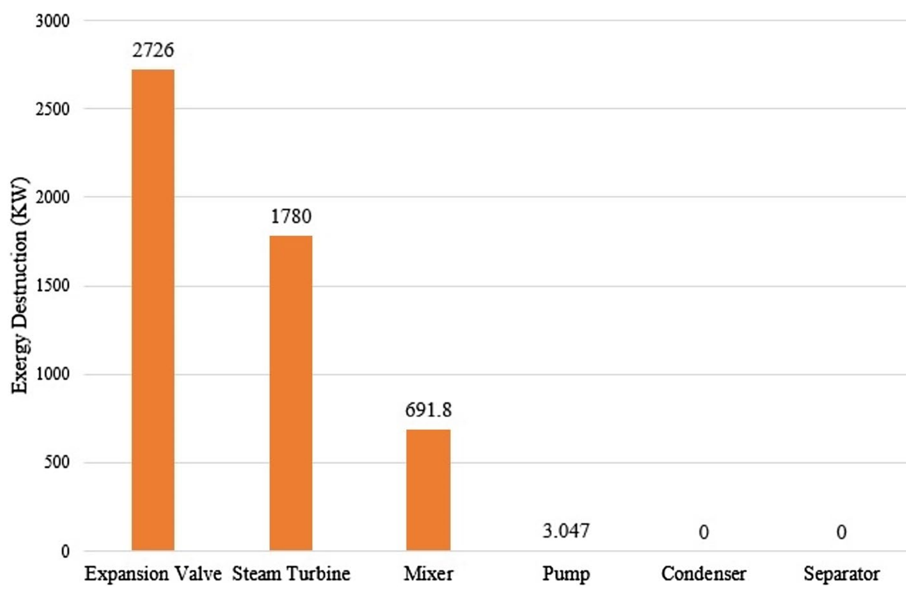


Fig. 2 Bar chart of splitting exergy destruction rates of components

Regarding the difference in the temperature value in point 8, it is also assumed that a mistake occurred in the article by Assad et al. 139 degrees Kelvin is a very low temperature, and probably the mentioned temperature should be Celsius, which is wrongly written as Kelvin. 139 degrees Celsius is almost equivalent to 412 Kelvin, which is not much different from the result of the present work.

Results and discussion

In this work, advanced exergy analysis for single flash geothermal cycle is performed and the results are presented in Tables 6 and 7, respectively. The first column of Table 6 shows the values of exergy destruction resulting from conventional exergy analysis. According to these results, in this cycle, the highest amount of exergy destruction is related to the expansion valve and then to the steam turbine, Mixer, Pump and condenser, respectively. As mentioned, heat loss and transfer is one of the important factors of irreversibility. It is not unreasonable to expect that the exergy loss in components in which heat loss is high and occurs at higher heat source temperatures is greater than in other components of the cycle. Therefore, the exergy is destroyed in the expansion valve more than other components of the cycle, because

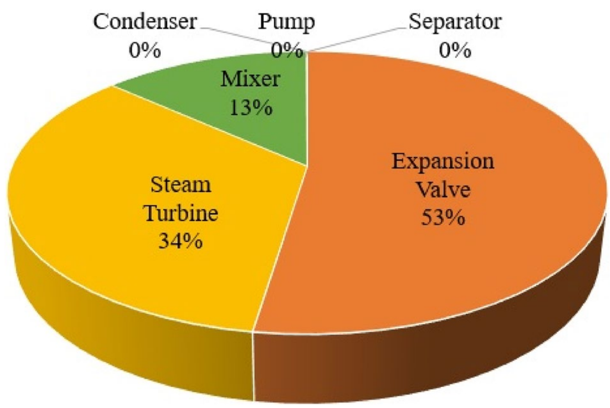


Fig. 3 Pie chart of exergy destruction rates of components

the amount of heat loss in this component is more than other components. In the case of moving components, such as turbine and pump, the efficiency, which is mostly due to friction, plays a key role in determining the amount of exergy destruction in these components.

In advanced exergy analysis, the effect of different system components on each other is determined by dividing the exergy destruction into endogenous and exogenous parts. In addition, by dividing the exergy destruction into avoidable and unavoidable parts, the part of the exergy destruction that is reduced as the system improves is determined.

Also, the results of Table 6 show that in all components of the cycle, the endogenous part of exergy destruction is more than the exogenous one. Therefore, the designer must focus more on the internal irreversibility of the component to improve its performance of those components. On the other hand, if the exogenous part is more than the endogenous part, it means that they are most affected by the inefficiency of other components, and the improvement in the performance of other components has the most positive effect on improving the performance of these two components.

Figure 2 shows the bar chart of the exergy destruction value of different system components. The highest amount of exergy destruction is in the expansion valve, with a value of 2726 kW. The steam turbine with 1780 kW and the mixer with 691.8 kW are in the next rank. Exergy destruction in the pump is a low amount of 3.087, and it is also very small in the condenser and separator. Figure 3 shows the circular diagram of exergy degradation of different components of the studied cycle. As it is known, expansion valve, steam turbine and mixer have the highest exergy destruction rate (Fig. 4).

The avoidable part is the destruction of the steam turbine and pump exergy from the inevitable part. In other words, it is possible to improve the efficiency of these components by applying new technical changes and technology, or replacing these components with more efficient components. An explanation of the important components of the cycle is given below.

Expansion Valve: The amount of exergy destruction of this component is 2726 KW.

Turbine: The amount of exergy destruction of this component is 1780 KW, of which 99% is endogenous and only 1% is exogenous.

Condenser: In this study, the exergy destruction in this component was very small.

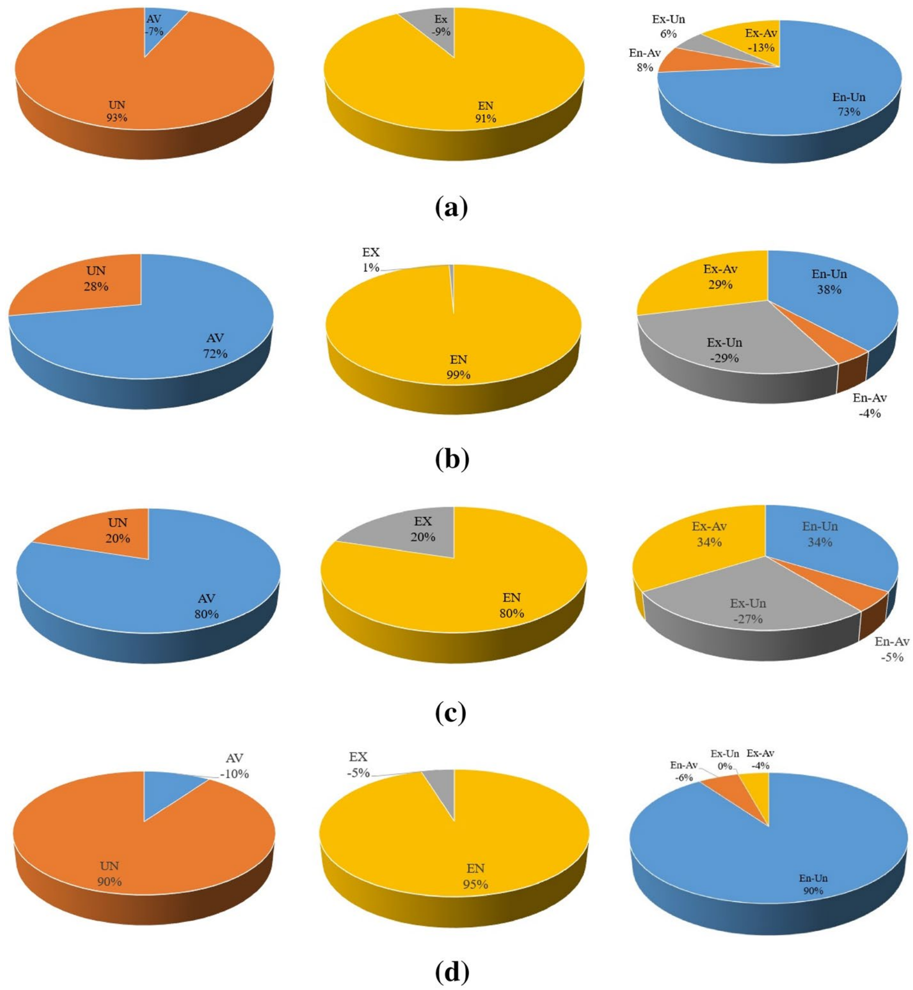


Fig. 4 Splitting exergy destruction rates of components: **a** Expansion valve, **b** steam turbine, **c** pump, and **d** mixer

Pump: Pump: The amount of exergy destruction of this component is 3.047 KW, of which 80% is endogenous and 20% is exogenous.

Separator: In this study, exergy destruction in this component was negligible.

Mixer: The amount of exergy destruction of this component is 691.8 KW.

According to Table 6, the elimination of endogenous-avoidable exergy in all equipment is smaller than the endogenous-unavoidable part ($E_{k,D}^{\mathrm{EN,UN}} > E_{k,D}^{\mathrm{EN,AV}}$). Improvement priority should be given to the pressure expansion valve based on the high amount of $E_{k,D}^{\mathrm{EN,AV}}$.

Figure 5 shows the bar chart of different parts of exergy destruction for all the system. In addition, in Fig. 6, the separation of exergy degradation of the whole cycle into endogenous, exogenous, unavoidable, avoidable, unavoidable and avoidable exogenous, and unavoidable and avoidable exogenous is shown graphically.

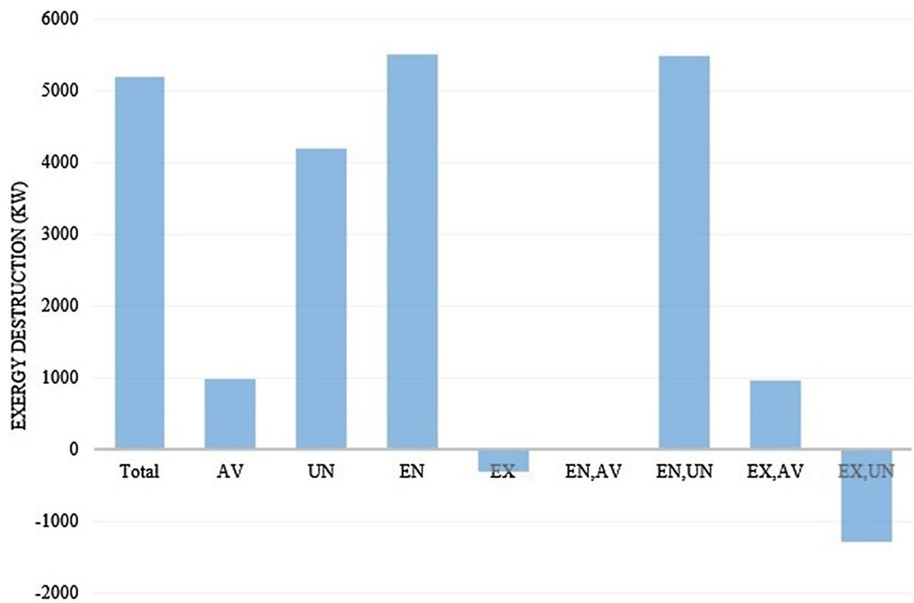


Fig. 5 Bar chart of different parts of exergy destruction for all the system

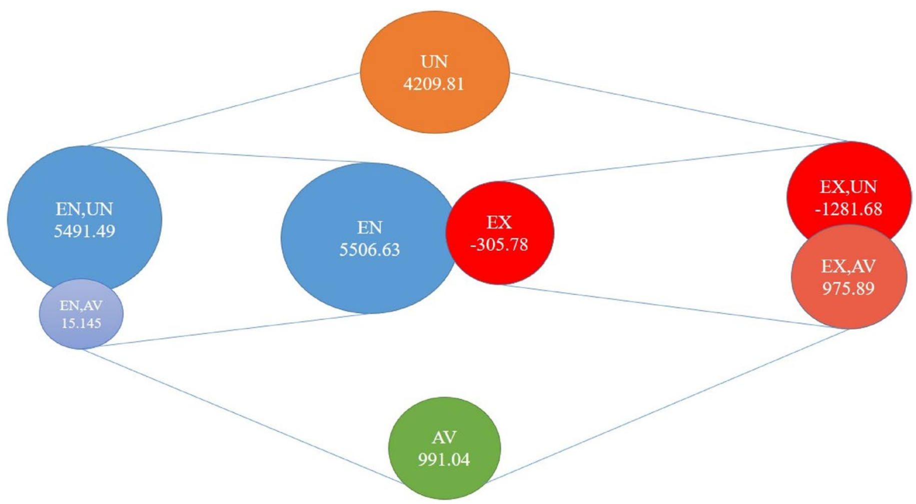


Fig. 6 Separation results of exergy destruction rates for the whole cycle

Conclusions

In the present paper, the flash single geothermal cycle has been studied from the perspective of conventional exergy analysis and advanced exergy analysis. In fact, advanced exergy analysis, by dividing exergy destruction into endogenous/exogenous and avoidable/unavoidable parts and combining them, identifies the amount and main source of irreversibility in a system and, such as thermos-economic analysis, helps in selecting more efficient system components. The results of this study are as follows:

- The total cycle exergy destruction is 5200.85 KW. From the point of view of ordinary exergy analysis, the highest exergy destruction of components is related to 2726 KW (53%), steam turbine with 1780 KW (34%) and mixer with 691.8 KW (13%).
- In terms of the achievable (avoidable) contribution of endogenous exergy destruction resulting from advanced exergy analysis, the real priority of recovery with pressure expansion valve (282 KW).
- The endogenous part of exergy degradation is greater than the exogenous part in all components of the cycle. As a result, to improve the performance of certain components, the designer must focus more on the component's internal irreversibility. If the exogenous part is greater than the endogenous part, it suggests that they are the most influenced by other components' inefficiency, and therefore, increasing the performance of other components has the most impact on improving the performance of these two components.
- The destruction of the steam turbine and pump exergy from the unavoidable part is the avoidable part. In other words, the efficiency of these components can be improved by implementing new technical innovations and technology, or by replacing them with more efficient components.

Abbreviations

$\dot{E}$	Exergy rate, in kilowatts
e	Specific exergy, in KJ per kg
$\dot{m}$	Mass flow rate, in kg per second
T	Temperature, in degree Celsius
$\dot{Q}$	Heat rate, in kilowatts
$\dot{W}$	Power, in kilowatts
P	Pressure, in MPa
H	Enthalpy, in KJ per kg
S	Entropy, in KJ per kg-K
COP	The coefficient of performance

Greek symbols

ε	Exergy efficiency

Superscripts

EN	Endogenous
EX	Exogenous
AV	Avoidable

Subtitles

i	Enter
e	Exit
D	Destruction
ph	Physical
Q	Heat
0	Dead state
R	Entrance
F	Fuel
P	Product
net	Network
tot	Total
th	Thermal
ex	Exergy
P	Pump
T	Turbine
Eva	Evaporator
Cd	Condenser

UN	Unavoidable
EN-AV	Endogenous-avoidable
EN-UN	Endogenous-unavoidable
EX-AV	Exogenous-avoidable
EX-UN	Exogenous-unavoidable

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Author contributions
XT: validation and formal analysis, GY: writing—review and editing, AMA: review and editing, ET-E: validation, review, and editing. AS: review and editing, YA: conceptualization, validation, writing, original draft, and visualization; JLGA: review and editing. All author read and approved the final manuscript.

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