

Research Article

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Performance evaluation of a geothermal-driven ejector power-cooling system: A comparative study of different refrigerants

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Highlights

- A geothermal-driven ejector power-cooling system was thermodynamically investigated.
- The effects of R134a, R1234yf, R1234ze(E), R600a, and R717 on system performance were comparatively evaluated.
- R600a achieved the highest net power output (324.5 kW) and exergy efficiency (32.98%).
- R717 provided the highest cooling capacity (344.7 kW) and energy efficiency (22.81%).
- The influence of geothermal source temperature on power, cooling, energy efficiency, exergy efficiency, and exergy destruction was comprehensively analyzed.

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ABSTRACT

The growing need for sustainable energy systems has increased research interest in energy systems capable of providing power and cooling from renewable energy resources. In this regard, a geothermal-assisted ejector refrigeration cycle (PERC) is developed and thermodynamically analyzed using five different working fluids, namely R134a, R1234yf, R600a, R1234ze(E), and R717. The performance characteristics are studied by conducting both energy analysis and exergy analysis on Engineering Equation Solver (EES). The impacts of various types of working fluids and geothermal source temperatures on net power production, cooling capacity, energetic efficiency, exergetic efficiency, and exergy irreversibility are carefully assessed in detail. Under the base operating condition of this novel power cycle, R600a produces the maximum net power output and exergy efficiency of 324.5 kW and 32.98%, respectively, while exhibiting the minimum exergy destruction of 660.8 kW. In contrast, R717 offers the maximum cooling capacity and energy efficiency of 344.7 kW and 22.81%, respectively. It can be observed from the parametric study that increasing the geothermal source temperature from 160 °C to 200 °C increases both the power and cooling output for all the working fluids. Higher source temperatures cause higher exergy destruction and lower exergy efficiencies because of greater irreversibilities within the system. It is thus concluded that the choice of working fluid plays an important role in determining the thermodynamic performance of the system. R600a has shown the highest exergy efficiency, while R717 has emerged as a better choice for cooling applications.

Keywords: Geothermal energy, Ejector power-cooling system, Energy and exergy analysis, Thermodynamic Performance, Refrigerants

INTRODUCTION

Energy is an essential component for the development of economies, industries, and enhanced living standards around the world. The constant increase in energy demand due to factors such as rapid urbanization, technological advancements, and population growth has created a high reliance on fossil fuels [1]. While it is true that fossil fuels have long been regarded as effective energy sources, their extensive use has been linked to several issues related to environmental degradation such as greenhouse emissions, global warming, climate change, and ozone depletion [2]. Besides, limited availability and varying price levels in fossil fuel markets have made scientists and engineers look into other energy technologies that are environmentally friendly [3]. Research conducted to solve this problem has shifted focus towards renewable energy sources and lower temperatures as ways to enhance energy conversion processes [4]. Renewable energy-based systems are highly valued as they not only help reduce negative impacts on the environment but also allow simultaneous energy production from the same source [5]. In this respect, the sources of thermal energy at low levels, including the sun, waste heat from industries, and geothermal energy, have received a great deal of attention over the last few years [6]. Geothermal energy, in particular, is among the most prospective energy sources within the sphere of renewable energies because of the reliable, clean, environmentally friendly, and climate-independent nature of this source of energy. In contrast to solar and wind energy systems, geothermal energy provides continuous energy supply regardless of the weather and season [7]. Moreover, geothermal energy sources offer significant prospects in terms of providing heat and electricity, air conditioning, water desalination, and many industrial purposes [8]. Therefore, geothermal energy is considered a promising renewable resource for meeting future energy demands while promoting environmental sustainability and reducing reliance on non-renewable energy resources.

Combined power and cooling cycles have attracted considerable attention in recent years because they enable concurrent production of electrical and cooling powers from a single source of heat with improved cycle efficiencies. In this regard, PERCs offer a promising solution, mainly due to their simplified design, ease of maintenance, high dependability, as well as capability to utilize low-quality energy sources [9]. Besides, the lack of moving parts within the ejector enables such systems to be effectively used in renewable energy sources-based systems. Thermodynamic performance of PERCs highly depends on the working fluid's thermophysical characteristics. Because of the increasing environmental issues related to the utilization of current refrigerants

with higher GWP values, a lot of studies have been conducted in search of new environmentally friendly refrigerants [10].

In this regard, there have been many studies focusing on ejector refrigeration cycles (ERC) from various angles like thermodynamics, exergy analysis, and economics, along with the selection of optimal working fluids. For instance, Saleh [11] modeled ejector driven low-grade heat-powered refrigerator cycle using thermodynamics and evaluated the efficiency of eight different refrigerants. It was found that R245ca provided a better coefficient of performance than other studied refrigerants. On the other hand, Dahmani et al. [12] presented a systematic approach to design ERC and carried out an evaluation study of R134a, R152a, R290, and R600a at varying operating conditions. Furthermore, Selvaraju and Mani [13] performed an analysis of ejector systems operating under the critical region and tested the performance of several environmental-friendly refrigerants such as R134a, R152a, R290, R600a, and R717, pointing out the significant impact of physical properties of selected refrigerant on ERC performance. Finally, Chen et al. [14] used energy, conventional, and advanced exergy analysis to assess an ERC using R600, R600a, R601a, R1233zd(E), and R1234ze(E). In another study, Gil and Kasperski [15] investigated a heat-source-powered ERC through various refrigerants and organic fluids and observed better thermodynamic performance for R236fa and cyclopentane. Moreover, Sun [16] conducted a detailed study on eleven different refrigerants such as water, halocarbons, and organic working fluids and found that the R152a had the highest coefficient of performance while steam-based refrigeration systems performed poorly. In addition to traditional ERCs, more emphasis has been placed on renewable energy sources for ejectors as well. For example, Xie and Zheng [17] proposed a novel geothermal based polygeneration cycle by incorporating transcritical CO₂ cycle and ERC to produce 435.9 kW of electricity and 251.5 kW of refrigeration effect simultaneously. In the same way, Ebadollahi et al. [18] designed a novel geothermal assisted triple evaporators ERC using three evaporators and a single ejector design and evaluated the thermodynamic, environmental, economic, and safety aspects of the plant. Similarly, Afzal and Ziapour [19] explored a renewable assisted ERC with thermal energy storage and phase change material application for building cooling.

Moreover, ejector cycles have been applied in combined power and refrigeration plants to optimize the use of renewable and waste energy sources. In this regard, Bao et al. [20] proposed a transcritical combined power and ERC operating on waste and renewable energy sources and

evaluated various working fluids based on their cooling effectiveness, power output, thermal efficiency, and exergy efficiency. Their results showed that R1234ze was the most efficient refrigerant based on both thermal and exergy performances. Naghibi Fard et al. [21] developed an ejector-vapor compression refrigeration cycle-based hybrid integrated refrigeration and electricity plant. Based on the thermodynamic and economic analyses, they found out that a mixture of R600-R1234yf had superior performance. Zhang et al. [22] introduced a novel PERC that incorporated a novel three-phase ejector of liquid, gas, and gas types for applications in ocean thermal energy conversion systems, showcasing significant improvements in cooling performance as well as generation of power compared to existing configurations. Li et al. [23] studied a geothermal-based multigeneration process consisting of an organic flash cycle and an ERC process and revealed that R141b yielded the largest cooling power, with a maximum value of 58.04 MW. Yang et al. [24] examined a PERC that used zeotropic blends and indicated that the maximum thermal and exergetic efficiencies were 10.77% and 10.29%, respectively, for an isobutane-pentane blend. Furthermore, Habibzadeh et al. [25] conducted a thermodynamic assessment of an integrated PERC using several working fluids and concluded that R601a provided the highest energy efficiency while simultaneously minimizing exergy irreversibility.

Although extensive research has been conducted on ERC and ejector-assisted PERCs, most existing studies have focused on either conventional refrigeration applications, organic Rankine cycle-integrated configurations, or multigeneration systems employing a limited number of working fluids. In addition, many previous investigations have primarily considered thermodynamic optimization or specific refrigerant selections without providing a comprehensive comparison of environmentally friendly refrigerants under identical operating conditions. Furthermore, studies examining geothermal energy-driven PERCs remain relatively scarce in the open literature. Particularly, a systematic thermodynamic assessment of low-GWP synthetic refrigerants and natural refrigerants in geothermal-based PERCs has not been sufficiently addressed. To the best of the authors' knowledge, studies providing a comprehensive comparison of R134a, R1234yf, R1234ze(E), R600a, and R717 in a geothermal-driven PERC are still very limited in the open literature. Therefore, the present study proposes a geothermal energy-driven PERC and performs a comprehensive thermodynamic investigation using R134a, R1234yf, R1234ze(E), R600a, and R717 as working agents. The impacts of refrigerant selection on refrigeration capacity, net power, energy efficiency, exergy efficiency, and total exergy destruction are systematically analyzed. The findings provide a comprehensive benchmark for evaluating the

thermodynamic performance of both synthetic and natural refrigerants under identical geothermal operating conditions. Furthermore, the results offer practical guidance for refrigerant selection in geothermal-driven ejector power-cooling systems by considering both power generation and cooling performance.

2. SYSTEM DESCRIPTION

Figure 1 illustrates the schematic configuration and thermodynamic state points of the proposed geothermal-driven ejector power-cooling system. As shown in the figure, geothermal energy is utilized as the primary thermal energy source to drive the PERC. The geothermal energy is transferred to the working agent in heat exchanger (HEX), and thus, the agent becomes ready for use in the PERC subsystem. The agent exits HEX at state 4 as superheated vapor; after that, the working fluid undergoes expansion in the turbine, and after producing power, it flows out of the turbine at state 5. The vapor exiting the turbine serves as the main flow into the ejector. The vapor leaving the evaporator at state 12 enters the ejector and serves as the secondary flow. The two vapor flows are mixed in the ejector and leave it at state 13; the mixture enters the mixer and then enters the recuperator (REC) at state 7. Heat exchange takes place in REC; the fluid exits REC at state 8 and enters the condenser. The compressed refrigerant stream splits into two streams after that. The first one goes through the expansion valve, which lowers the pressure to state 11 before the refrigerant enters the evaporator. The evaporator uses heat exchange processes to take heat from the cooling load and produce refrigeration. As a result, the gas refrigerant exits the evaporator at state 12 and flows back to the ejector. The second branch of the cooled refrigerant goes through the pump, where it is compressed at state 1. After that, the compressed refrigerant exits the pump at state 2 and enters the recuperator. Inside the REC, the refrigerant is preheated using the heat from the hot stream, which is discharged from the ejector. After exiting the recuperator at state 3, the gas enters HE1, which heats up the refrigerant due to geothermal energy. The hot refrigerant exits HEX at state 4 and flows to the turbine, thus completing the thermodynamic cycle.

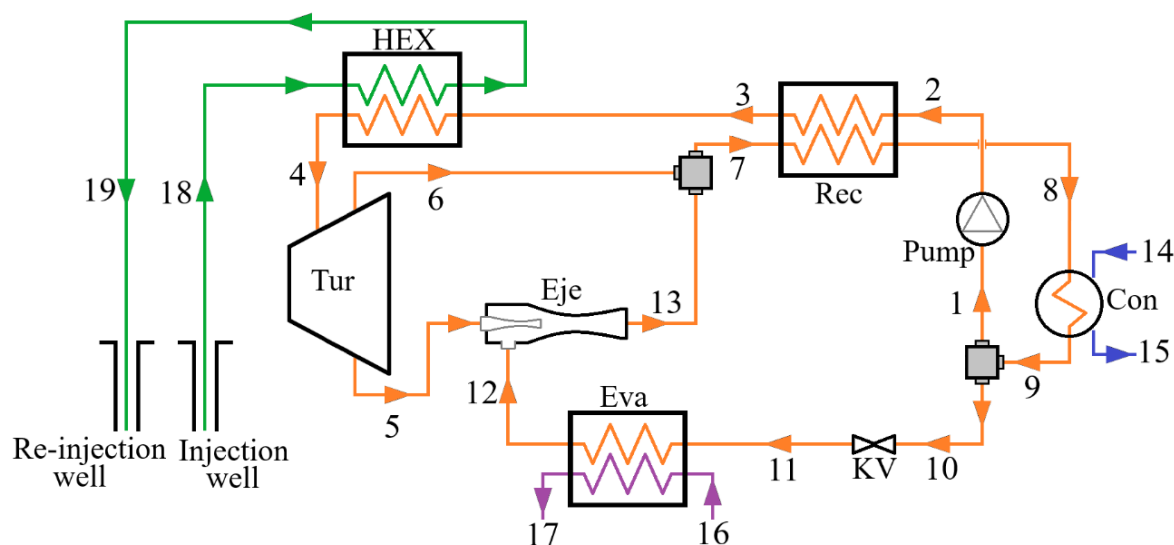


Figure 1. Schematic diagram of the geothermal energy-driven PERC

3. THERMODYNAMIC MODELING

The thermodynamic modeling of the proposed geothermal energy-assisted ERC was performed using the EES software package. The energy and exergy analysis of the proposed geothermal-driven PERC was carried out based on energy, mass, and exergy balances of the plant's different components. Furthermore, the effects of different working fluids on refrigeration capacity, net power output, energy efficiency, exergy efficiency, and exergy destruction were investigated. To simplify the problem statement, the following assumptions were considered.

- Steady-state and steady-flow conditions prevail throughout the system.
- Heat losses and pressure drops in the plant components are negligible.
- One-dimensional steady flow is assumed within the ejector nozzle and diffuser.
- Kinetic and potential energy changes are negligible.
- The inefficiencies of the nozzle, mixer, and diffuser are represented by their respective efficiencies.
- The mixing process in the ejector takes place under constant pressure conditions and fulfills the principles of conservation of mass, momentum, and energy.
- The outlet of the condenser and that of the evaporator are considered to be saturated liquid and saturated vapor, respectively.
- The reference condition for the purpose of exergy analysis is considered as $T_0 = 25\text{ }^{\circ}\text{C}$ and $P_0 = 101.325\text{ kPa}$.

The thermodynamic analysis of the plant is based on the principles of mass and energy conservation. The governing equations for mass and energy conservation are given as follows [26]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} + \dot{W} \quad (2)$$

In these equation, $\dot{m}$ denotes the mass flow rate and h represents the specific enthalpy. In addition, $\dot{Q}$ and $\dot{W}$ correspond to the rates of heat transfer and power generation, respectively. The exergy balance for the system can be expressed as follows [26]:

$$\dot{Ex}_Q + \sum \dot{m}_{in} ex_{in} = \sum \dot{m}_{out} ex_{out} + \dot{Ex}_W + \dot{Ex}_D \quad (3)$$

Here, ex denotes the specific exergy and $\dot{Ex}_D$ indicates the rate of exergy destruction. Furthermore, $\dot{Ex}_Q$ and $\dot{Ex}_W$ denote the exergy transfer rates related to heat and work, respectively. The mathematical relations between these parameters are stated below [26]:

$$ex = (h - h_0) - T_0(s - s_0) \quad (4)$$

$$\dot{Ex}_W = \dot{W} \quad (5)$$

$$\dot{Ex}_Q = \dot{Q} \left(1 - \frac{T_0}{T_k} \right) \quad (6)$$

$$\dot{Ex}_D = T_0 \dot{S}_{gen} \quad (7)$$

where, s is the specific entropy, while $\dot{S}_{gen}$ is the entropy production. The subscripts "0" and "k" denote the environmental reference state and the heat source temperature, respectively.

The plant's efficiency on the basis of energy and exergy considerations can be mathematically expressed as:

$$\eta_{en} = \frac{\dot{W}_{net} + \dot{Q}_{eva}}{\dot{m}_{18}h_{18} - \dot{m}_{19}h_{19}} \quad (8)$$

$$\eta_{ex} = \frac{\dot{W}_{net} + \dot{E}x_{\dot{Q}_{eva}}}{\dot{m}_{18}ex_{18} - \dot{m}_{19}ex_{19}} \quad (9)$$

To validate the developed thermodynamic model, the predicted refrigeration capacity and net power output were compared with the corresponding results reported in Ref.[27] under the same operating conditions. As illustrated in Figure 2, the present model predicted a refrigeration capacity of 21.89 kW and a net power output of 116.97 kW, whereas the reference study reported values of 21.02 kW and 114.10 kW, respectively. The deviations between the present and reference results were found to be 4.16% for refrigeration capacity and 2.52% for net power output. The deviations are within an acceptable range, indicating good agreement between the present model and the reference study. These results confirm that the developed model is capable of accurately predicting the thermodynamic performance of the PERC system. Therefore, the validated model provides a reliable basis for the subsequent parametric analysis and refrigerant comparison presented in this study.

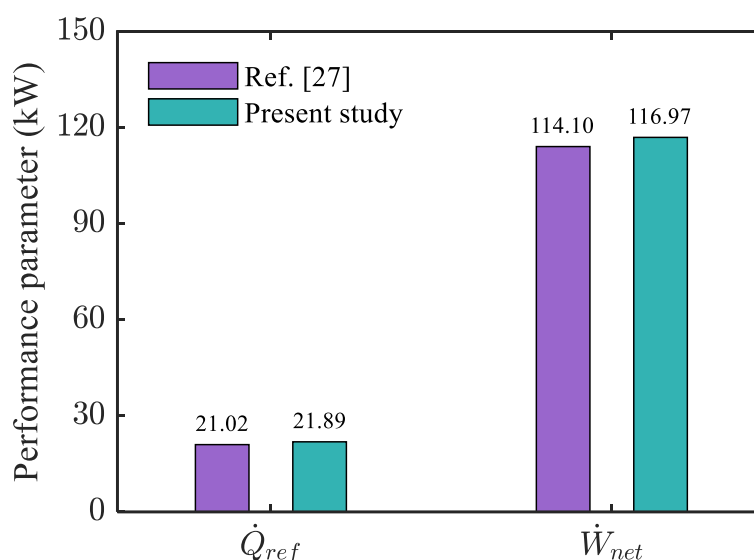


Figure 2. Validation of the ERC Model

4. RESULTS AND DISCUSSION

The plant's thermodynamic performance is analyzed based on its reference operating condition. All simulations have been carried out by using EES. The assumptions made while conducting

simulation are highlighted in Table 1. The simulation results are discussed in two parts. Firstly, the cycle's performance is analyzed in terms of the following parameters: cooling capacity, net power output, thermal efficiency, exergetic efficiency, and irreversibility. Secondly, the effect of geothermal fluid temperature and flow rate on the plant's performance is explored.

Table 1. Main design parameters in the plant model [28]

Parameters	Values
Geothermal resource temp. (°C)	180
Geothermal mass flow rate (kg/s)	5
Evaporator temp. (°C)	5
Condenser temp. (°C)	27
Turbine isen. efficiency (%)	82
Pump isen. efficiency (%)	80
Ejector entrainment ratio	0.4

Figure 3 shows the net power and refrigeration capacity variations with different working fluids used in the suggested geothermal-based PERC. The findings show that the agent's selection is vital in both power production and refrigeration systems. Of the studied refrigerants, R600a has the highest net power value of 324.5 kW, then R1234yf (319.8 kW) and R134a (315.5 kW). On the other hand, refrigerants R1234ze (E) and R717 have relatively low net power output values of 309.2 kW and 309.9 kW, correspondingly. The highest refrigeration capacity value is recorded with R717 at 344.7 kW. The cooling capacities obtained with R134a, R600a, and R1234ze(E) are 293.7 kW, 284.8 kW, and 282.7 kW, respectively, whereas R1234yf results in the lowest cooling capacity of 274.2 kW. Compared with the reference refrigerant R134a, the use of R717 increases the cooling capacity by approximately 17.4%, while reducing the net power output by nearly 1.8%. These results reveal a trade-off between power generation and cooling. Although R600a demonstrates superior performance in terms of net power output, R717 offers the most favorable refrigeration performance. Therefore, the selection of the working agent should be made according to the desired balance between refrigeration demand and electricity generation in geothermal-driven PERCs. The observed differences are mainly attributed to the distinct thermophysical properties of the refrigerants, which influence the energy conversion processes within the cycle. Consequently, refrigerant selection directly affects the balance between power generation and cooling performance.

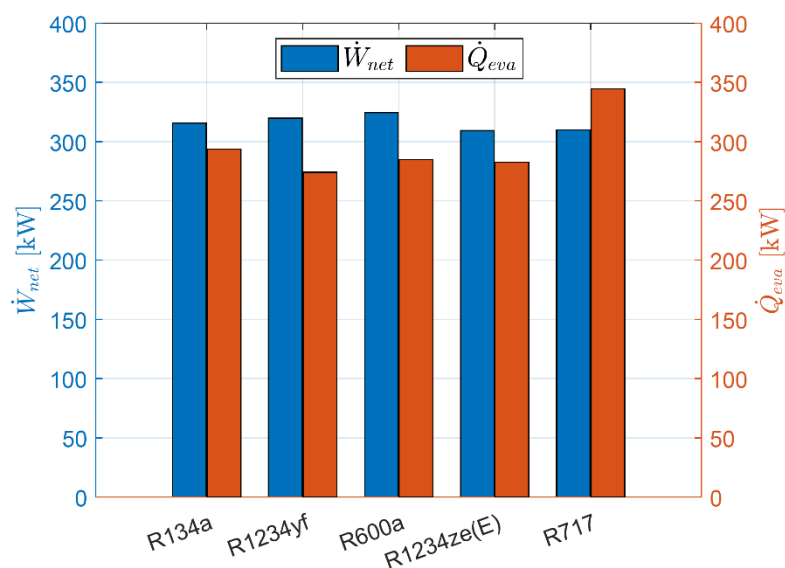


Figure 3. Comparison of net power and cooling capacity

Figure 4 illustrates the variation of energetic and exergetic efficiencies for the considered working fluids. The obtained results reveal relatively small differences in energetic performance among the refrigerants, with efficiency values ranging from 20.63% to 22.81%. The most favorable energetic performance is achieved with R717, whereas R1234ze(E) exhibits the lowest energy efficiency. R134a, R1234yf, and R600a display comparable energetic behavior, indicating a limited influence of refrigerant selection on the first-law performance of the system. A greater variation is observed in the exergy efficiency values. R600a achieves the highest exergy efficiency of 32.98%, followed by R717 and R1234yf. On the other hand, R1234ze(E) shows the least exergy efficiency value of 31.29%. The high exergy efficiency of R600a indicates more effective utilization of the available energy. This behavior can be attributed to the thermodynamic characteristics of the refrigerant, which reduce irreversibility during the heat transfer and expansion processes. The relatively lower exergy efficiency of R1234ze(E) can be explained by higher exergy losses in the cycle. Considering the energetic and exergetic efficiencies, it is apparent that R717 and R600a could be considered the best refrigerants because they offer maximum energy and exergy efficiencies, respectively. These results indicate that the optimal refrigerant depends on whether energy or exergy performance is prioritized.

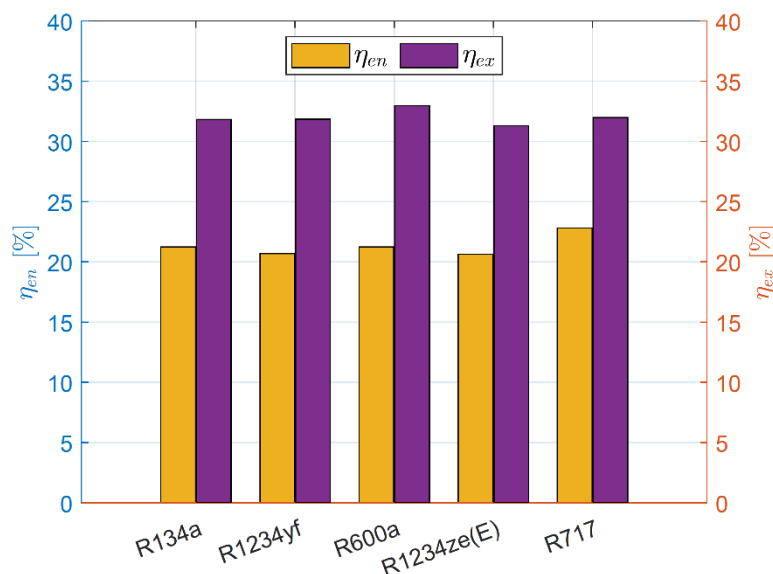


Figure 4. Comparison of energy and exergy efficiencies

Figure 5 illustrates the component-wise exergy destruction for the investigated refrigerants. It is evident that the heat exchanger is the dominant source of exergy destruction for all refrigerants, with values ranging from 435.8 to 518.2 kW. Among the investigated fluids, R717 exhibits the highest exergy destruction in the heat exchanger (518.2 kW), whereas R1234yf shows the lowest value (435.8 kW). The turbine represents the second largest source of irreversibility, with exergy destruction varying between 57.3 and 65.8 kW. The ejector, condenser, and recuperator also contribute significantly to the overall irreversibility, while the pump and expansion valve account for the smallest exergy destruction, remaining below approximately 8 kW and 4 kW, respectively. In addition, the evaporator exergy destruction varies within a relatively narrow range of 17.5–22.0 kW for all working fluids. These results indicate that the distribution of irreversibilities strongly depends on the selected refrigerant, with the heat exchanger and turbine being the major contributors to the total exergy destruction. Accordingly, the total exergy destruction values are 670.1, 665.4, 660.8, 675.9, and 676.1 kW for R134a, R1234yf, R600a, R1234ze(E), and R717, respectively, indicating that R600a exhibits the lowest overall irreversibility among the investigated refrigerants. Therefore, performance improvement efforts should primarily focus on reducing irreversibilities in the heat exchanger and turbine to enhance the overall exergetic performance of the system.

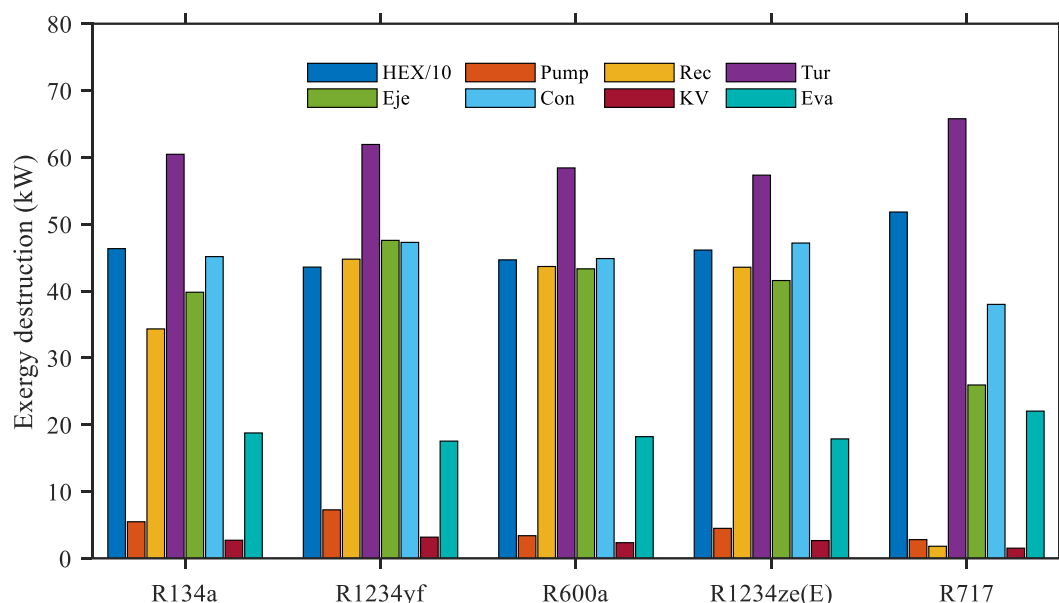


Figure 5. Comparison of exergy destruction in individual system components for different refrigerants (heat exchanger values are divided by 10 for visualization purposes)

Figure 6 displays the net power variation with geothermal source temperature for various working fluids. As expected, increasing the geothermal resource temperature results in higher net power output for all refrigerants due to the increased thermal energy input. For all working fluids analyzed, an almost linear raises in electricity can be seen when the injection well temperature is varied from 160 °C to 200 °C. Amongst all the refrigerants analyzed, R600a shows the maximum net power for almost the entire range of temperature variation. The net power of R600a raises from 261.2 kW at 160 °C to 394.1 kW at 200 °C, representing an increase of about 50.9 %. A similar pattern is seen for R1234yf, which increases from 251.7 kW to 394.5 kW at 160 °C and 200 °C respectively. However, at high geothermal temperatures, R1234yf performs marginally better than R600a, with an output value of 394.5 kW compared to 394.1 kW for R600a at 200 °C. On the contrary, the net power generated by R1234ze(E) and R717 is relatively low at all temperatures analyzed. When the geothermal source temperature is 200°C, the net powers produced using R1234ze(E) and R717 as the refrigerant are 375.5 kW and 378.4 kW, correspondingly. It is evident from the results that the geothermal source temperature plays a vital role in the power generation process. Increasing the geothermal temperature raises the available thermal energy supplied to the working fluid, resulting in a larger enthalpy drop across the turbine and, consequently, higher net power output. Furthermore, the different thermophysical properties of the refrigerants become more influential at elevated source temperatures, leading to more pronounced differences in power generation.

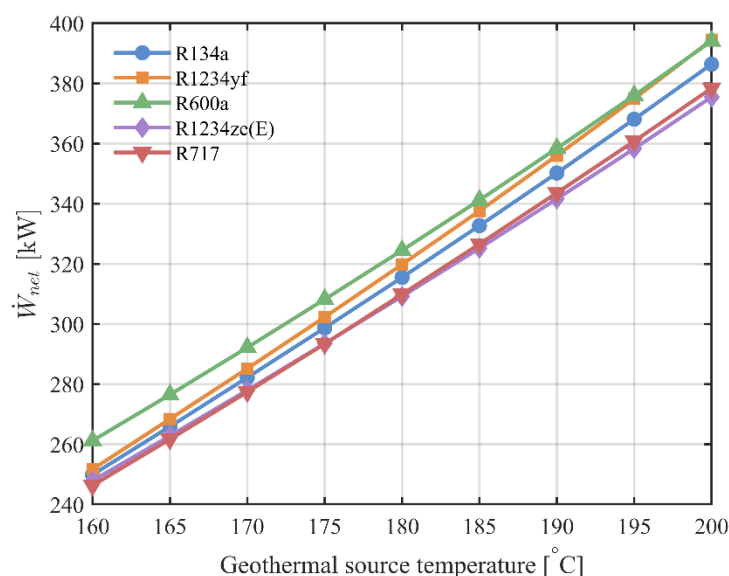


Figure 6. Variation in net power with geothermal source temperature

Figure 7 presents the variation of the cooling capacity with respect to geothermal resource temperature for the studied working agents. The higher the injection well temperature is, the better the raise in cooling capacity will be for all of the refrigerants examined. This trend occurs because of the improvement in the amount of thermal energy input into the plant that leads to the enhancement of the ejector performance, and thereby improving in the refrigerating effect achieved through the evaporator process. The cooling capacity exhibits a different trend from the net power output. The differences among the refrigerants are more pronounced for net power output than for cooling capacity. At any temperature level, R717 exhibits the best cooling performance among all refrigerants studied. The value of the cooling capacity of R717 is improved from 299.6 kW at 160 °C to 388.8 kW at 200 °C, representing an increase of around 29.8%. This outstanding performance of ammonia refrigerant can be linked to its excellent ability for refrigeration under geothermal conditions. This behavior is mainly attributed to the favorable thermophysical properties of R717, which enhance heat absorption in the evaporator and improve the refrigeration effect. For instance, R134a offers the next best performance after R717 with respect to cooling capacity. For R600a and R1234ze(E), comparable tendencies are observed; their cooling performance peak at values of 321.9 kW and 317.2 kW, respectively, under the maximum examined temperature. On the other hand, R1234yf shows the lowest cooling performance in all examined temperatures, ranging from 243.0 kW at 160 °C to 307.8 kW at 200 °C. From the results presented above, it can be observed that an increase in geothermal temperature significantly

increases the cooling capacity of the system, irrespective of the working fluid selected. Additionally, a clear gap is observed between R717 and the rest of the refrigerants as the geothermal temperature increases.

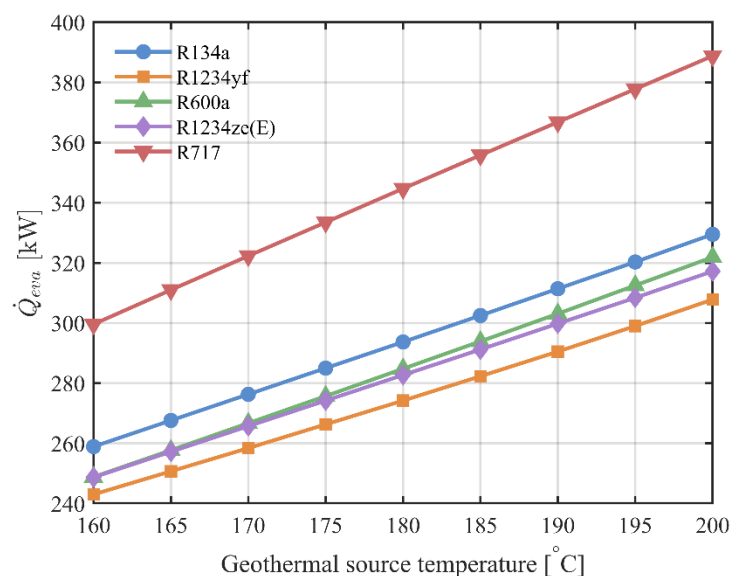


Figure 7. Variation in cooling capacity with geothermal source temperature

Figure 8 illustrates the variation in total exergy destruction with geothermal source temperature for the investigated working fluids. A significant increase in exergy destruction is observed as the geothermal source temperature increases. This trend is attributed to the increase in thermal energy input and the larger temperature differences occurring within the system components, which intensify the associated irreversibilities. Over the entire temperature range, exergy destruction increases approximately linearly for all refrigerants. R717 and R1234ze(E) generally exhibit the highest exergy destruction values. For R717, the total exergy destruction increases from 516.7 kW at 160 °C to 850.9 kW at 200 °C, while the corresponding values for R1234ze(E) increase from 515.1 kW to 852.2 kW. R600a and R1234yf generally exhibit lower exergy destruction values, ranging from 501.8 kW to 833.7 kW and from 511.2 kW to 833.2 kW, respectively. For R134a, the exergy destruction increases from 513.3 kW to 841.9 kW over the same temperature range. The relatively high exergy destruction values obtained for R717 and R1234ze(E) indicate greater degradation of the available energy within the cycle. This behavior is associated with the different thermophysical properties of the refrigerants, which affect heat transfer and expansion processes and, consequently, the magnitude of irreversibilities throughout the system. Therefore, refrigerants exhibiting lower irreversibility levels also result in lower total exergy destruction. Although increasing the geothermal source temperature enhances both net power output and cooling

capacity, it also leads to higher exergy destruction because of the increased thermal energy input and larger temperature differences within the system components.

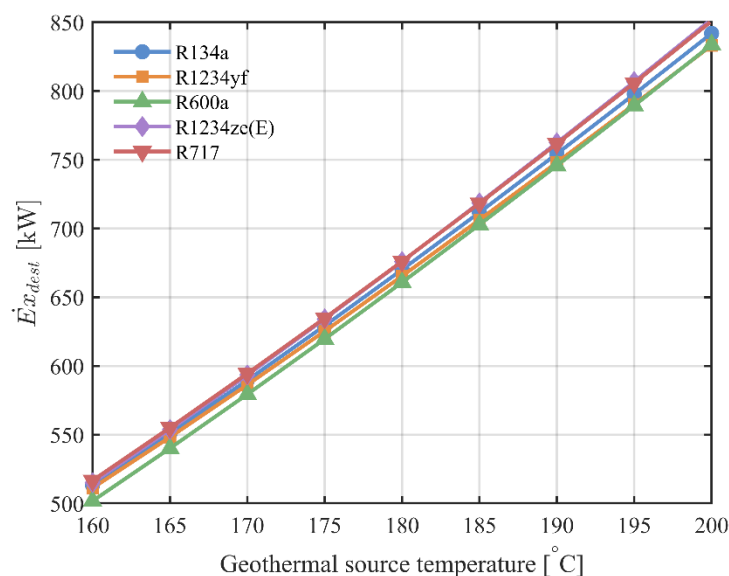


Figure 8. Variation in exergy destruction with geothermal source temperature

As can be seen in Figure 9, the variation of energy efficiency with geothermal source temperature is presented for the investigated working fluids. It can be observed that the energy efficiency increases slightly with increasing geothermal source temperature for all the investigated refrigerants. This trend is mainly attributed to the increase in useful energy outputs, including net power output and cooling capacity, resulting from the greater thermal energy input. Among the investigated refrigerants, R717 achieves the highest energy efficiency, increasing from 22.44% at 160 °C to 23.16% at 200 °C, corresponding to an increase of approximately 3.2% relative to the initial value. The relatively small improvement in energy efficiency is attributed to the simultaneous increase in both the useful energy output and the geothermal energy supplied to the system. As the geothermal source temperature increases, the additional thermal energy supplied to the system is accompanied by a comparable increase in net power output and cooling capacity. Consequently, the ratio of useful energy output to energy input changes only slightly, resulting in only a modest improvement in the overall energy efficiency. In contrast, R1234ze(E) exhibits the lowest energy efficiency, with values ranging from 20.41% to 20.91%. At 200 °C, the energy efficiency values of R134a and R600a are both 21.61%, while that of R1234yf is slightly lower at 21.20%. Although the influence of geothermal source temperature on energy efficiency is less pronounced than its influence on net power output and cooling capacity, the results indicate that

higher geothermal source temperatures improve the overall energy performance of the system. Among the investigated refrigerants, R717 exhibits the best overall energy performance.

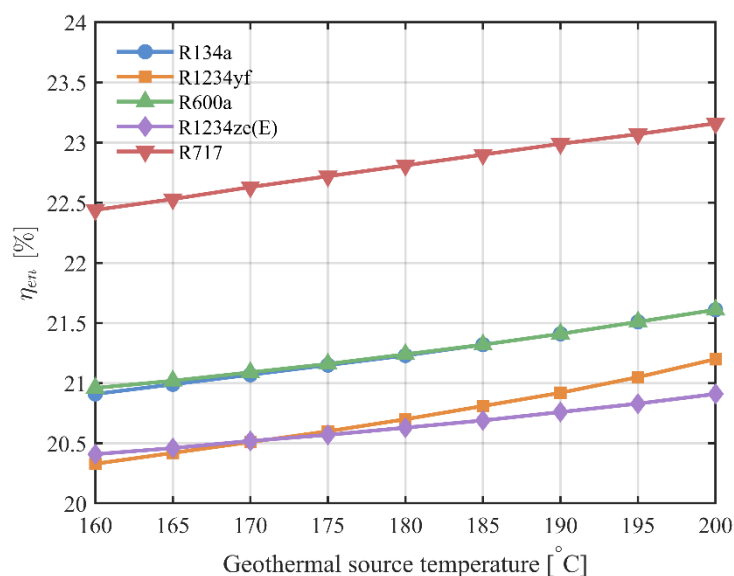


Figure 9. Variation in energy efficiency with geothermal source temperature

The variation of exergy efficiency in relation to geothermal source temperature is given in Figure 10 for all the working fluids used in this study. Contrary to the trend shown in the energy efficiency graph, the exergy efficiency decreases gradually with an increase in the geothermal source temperature from 160 °C to 200 °C. This decline can be attributed to the higher amount of exergy input provided by the geothermal source, thus causing an increase in irreversibilities within the system components. The extent of this reduction varies among the refrigerants because their thermophysical properties affect heat transfer and expansion processes and, consequently, the magnitude of irreversibilities throughout the system. Therefore, refrigerants exhibiting lower irreversibility levels also achieve higher exergy efficiencies. Of all the refrigerants analyzed, R600a maintains the highest exergy efficiency throughout the temperature range. The exergy efficiency of R600a declines from 34.26% at 160 °C to 32.14% at 200 °C. This efficiency is still higher than that of the other working fluids. R717 demonstrates better exergy performance at lower geothermal temperatures, having an exergy efficiency of 32.86% at 160 °C but declining to 31.28% at 200 °C. On the other hand, the poorest exergy performance is observed for R1234ze(E), whose efficiency decreases from 32.37% to 30.51%. The exergy efficiency of both R134a and R1234yf also decreases, resulting in 31.29% for R134a and 31.57% for R1234yf at 200 °C. While an increase in geothermal temperature results in an increase in net power output and cooling

capacity, the associated increase in exergy destruction leads to a reduction in the overall exergy efficiency. This implies that an increase in geothermal temperature improves the amount of useful product but not the quality of energy transformation. In general, it can be stated that R600a is the optimal choice among all the refrigerants from the exergy point of view.

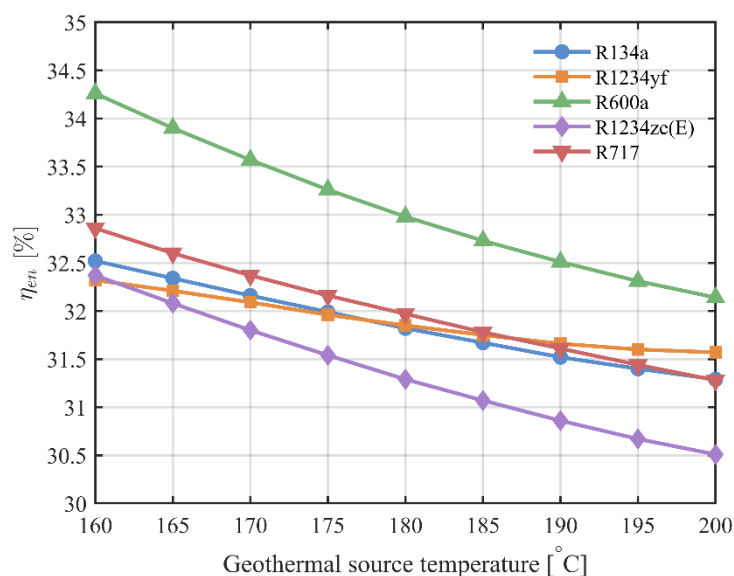


Figure 10. Variation in exergy efficiency with geothermal source temperature

Although R600a and R717 exhibit superior thermodynamic performance, practical implementation should also consider environmental and safety aspects. R600a offers excellent thermodynamic characteristics and a very low GWP; however, its high flammability (A3 classification) may limit its application in certain systems. Similarly, R717 provides zero a GWP and outstanding cooling performance but requires appropriate safety measures because of its toxicity. In contrast, R1234yf and R1234ze(E) represent environmentally friendly alternatives with low GWP values, making them attractive candidates where environmental regulations are of primary importance. Therefore, refrigerant selection should be based not only on thermodynamic performance but also on safety requirements, environmental considerations, and the intended application.

5. CONCLUSIONS

The current research involved the thermodynamic analysis of a geothermal-based PERC using five different types of working fluids such as R134a, R1234yf, R600a, R1234ze (E), and R717. The performance characteristics of the proposed geothermal-driven ejector power-cooling system were

examined through energy and exergy analyses. The major conclusions drawn from the present study are summarized as follows:

- The choice of working fluid highly influenced the thermodynamic characteristics of the system.
- Of all the examined refrigerants, R600a showed the best thermodynamic behavior since it gave the maximum value of net power generation (324.5 kW) and highest exergy efficiency (32.98%) coupled with minimal exergy destruction (660.8 kW).
- Among the studied refrigerants, R717 displayed superior performance in cooling operation with a cooling capacity of 344.7 kW and energy efficiency of 22.81%.
- Among all other refrigerants used in this study, R1234ze(E) revealed inferior energy and exergy efficiencies, while R1234yf showed intermediate performance in terms of these parameters.
- An increase in the geothermal source temperature from 160 °C to 200 °C led to the increase in net power and cooling capacity of all working fluids under consideration. There was a rise in net power output by 48–57% and cooling capacity by 27–30%, depending on the refrigerants used.
- The improvements in power generation and cooling performance did not have a positive impact on exergy destruction and exergy efficiency, which were adversely affected by the increase in irreversibilities within the system.
- The maximum net power output was achieved for R1234yf and R600a at high geothermal source temperatures, while R717 was found to be the most efficient refrigerant in terms of cooling capacity over the entire temperature range studied.

On the whole, the outcomes suggest that R600a exhibits the best thermodynamic performance in terms of exergy efficiency while R717 appears to be more attractive from the viewpoint of cooling generation and energy efficiency. The presented information may be helpful in selecting suitable refrigerants for geothermal PERCs. Furthermore, although the present study focused on the influence of geothermal source temperature, other operating parameters, such as condenser temperature, evaporator temperature, turbine isentropic efficiency, and ejector entrainment ratio,

may also significantly affect the thermodynamic performance of the system. A comprehensive investigation of these parameters is recommended for future studies to provide a more complete assessment of geothermal-driven ejector power-cooling systems.

DECLARATION OF ETHICAL STANDARDS

The author declares that no ethical committee approval and/or special legal permission was required for this study.

CONTRIBUTION OF THE AUTHORS

Serpil Celik Toker: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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