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Thermodynamic Analysis of New Cogeneration Cycle Based on Gaynarje Hotspring

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ABSTRACT

Gaynarje spring is one of the hottest springs in the world and is located around Meshginshahr in northwest of Iran. Because of the water at temperature of 82 ºC, it is not appropriate to use this mineral water for swimming and bathing. In this study, in addition to lowering the water temperature to the appropriate swimming temperature (29 ºC), the hot water is used for power and natural gas production in a combined cycle based on Organic Rankine Cycle (ORC) and LNG cold. The proposed configuration has been studied thermodynamically and optimized for important performance parameters. For this purpose, mass, energy and exergy equations were developed for components and the whole system. Also, performance parameters were calculated. For achieving the best results, several working fluids are examined for the ORC. According to the obtained results R245fa as an ORC working fluid has the best performance from the thermodynamic viewpoint. Also, for optimum condition of the cogeneration cycle, net output power, natural gas production, thermal and exergy efficiencies were calculated to be 524.9 kW, 1.352 kg/s, 24.11 and 48.99%, respectively. The parametric study is also indicated that the performance parameters have optimum values with respect to the evaporator temperature.

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NOMENCLATURE

$\dot{E}$	Exergy rate (kW)	$\dot{W}$	Power (kW)
h	Specific enthalpy (kJ/kg)	**Greek Symbols**	
LNG	Liquefied Natural Gas	η_{ex}	Exergy efficiency (%)
$\dot{m}$	Mass flow rate (kg/s)	η_{th}	Thermal efficiency (%)
ORC	Organic Rankine Cycle	**Subscripts**	
P	Pressure (kPa)	Ev	Evaporator
$\dot{Q}$	Heat transfer rate (kW)	P	Pump, product
T	Temperature (°C), Turbine	PP	Pinch point

1. INTRODUCTION

Nowadays, the demand for energy and electricity in the industrial, commercial and service sectors has increased, which has led to an increase in fossil fuel consumption [1-5]. This trend leads to environmental pollution and energy shortages. In order to avoid these effects, many studies have recently been conducted on the use of low-grade heat sources, including geothermal energy source [6,7]. Fallah et al. [8] performed a comparative analysis on single, double, and triple-flash, dry steam and different Organic Rankine Cycle (ORC) configurations for power generation from geofluid temperature of 230 ºC. They showed that the triple-flash system produces more power compared to the single and double-flash from the thermodynamic viewpoint while the dry steam cycle is the best cycle from thermoeconomic point of view. A new configuration of integrated single and double-flash with modified Kalina is proposed by

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Mokarram and Mosaffa [9], who reported for the optimum operating condition that the double flash/modified Kalina produces about 6% more power compared to the basic cycle.

Natural gas as a fossil fuel is used extensively because of low global warming potential and high level of energy production. Liquefied Natural Gas (LNG) can release a lot of energy in the regasification process [10,11]. For geothermal temperature of 443.15 K and LNG cold energy recovery with the cascade Kalina/Kalina, the performance of combined cycle from the thermodynamic and exergoeconomic viewpoints is analyzed by Gaebi et al. [12], who reported an optimum net power of 9044 kW, a thermal efficiency of 29.87% and a total product unit cost of $127.8/GJ for the cycle. Four combined LNG cold energy and ORCs are investigated by Mosaffa et al. [13] from the thermo-economic point of view. They showed that the lowest total product cost as well as the maximum net power output belong to the simple ORC and dual-fluid system, respectively. Sadreddini et al. [14] examined a cascade transcritical CO_2 and ORC to recover energy from the medium temperature LNG heat source. They showed that the exergy efficiency of the transcritical CO_2 cycle is calculated to be 11.24% while this value is 12.3% for ORC. Also, they reported that pentane as a working fluid has the best performance for the cascade cycle. Ahmadi Boyaghchi and Safari [15] analyzed the cogeneration cycle involved a proton exchange membrane electrolyzer, a LNG vaporization process and a cascade ORC utilizing geothermal energy. They showed that total avoidable investment cost rate is improved about 17.4% relative to the base point.

Mount Sabalan is located in northwest of Iran and has been involved in creation of hotsprings in and around Sareyn and Meshginshahr cities. A hotspring is a spring produced by the emergence of geothermally heated groundwater that rises from the Earth's crust. The Sabalan geothermal power plant is also under development in this region [16-18]. One of the hottest springs in Sabalan field and in the world is the Gaynarje hotspring at temperature of 82 °C. This spring is located in 38° 17' 23" North and 47° 41' 19" East.

Due to high temperature of Gaynarje spring, 82 °C, it is not suitable for swimming and bathing. In this study, a new cycle is proposed for generating power based on ORC and LNG cold energy. Also,the LNG subsystem can supply the gas demand of complex and around. Eventually, the hotspring water is brought to the proper swimming temperature by losing its energy. Mass, energy and exergy relations were applied to the system compoents and the whole system. Then, the performance parameters are determined. Three working fluids are considered for ORC to achieve the best results. Also, the sensitivity of the system response to the important parameters are discussed. It is remarkable that, to our best of knowledge, no studies have been conducted on the use of hotsprings for power generation. In summary, these aims are followed in this study:

- Using Gaynarje hotspring real thermodynamic data for power and LNG
- Bringing t Gaynarje hot water temperature to a suitable swimming temperature
- Supplying complex and its surrounding natural gas demand
- Producing power by ORC and LNG based proposed system
- Analysing the proposed system from energy and exergy viewpoints
- Performing a comprehensive parametric study to investigate the effects of important parameters on the performance of the proposed system

2. SYSTEM DESCRIPTION

Figure 1. shows the schematic diagram of the proposed system that uses Gaynarje hotspring as the heat source. As this figure indicates, the LNG subsystem is used to produce power (in a turbine) and as a heat sink for ORC. In addition to produce the natural gas and power, the proposed system provides hot water with a suitable temperature for swimming usage. The saturated liquid from Gaynarje hotspring (state 1) enters to the ORC evaporator where the ORC fluid temperature increases

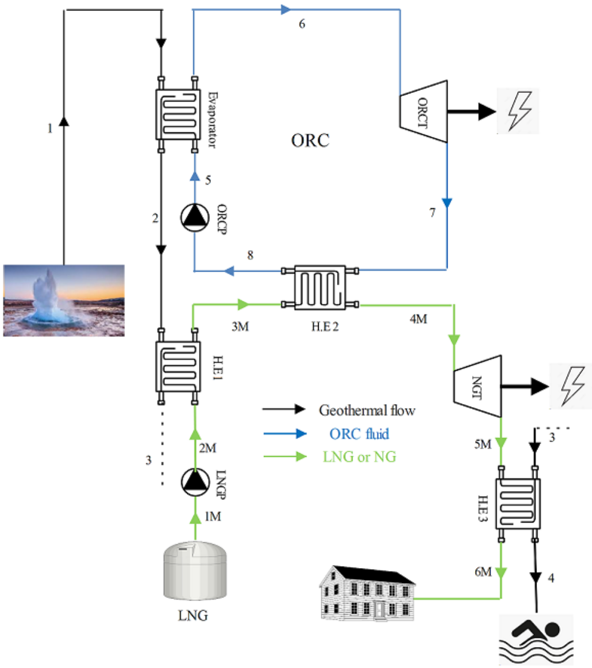

Figure 1. Schematic diagram of the proposed system based on Gaynarje hotspring

(state 6), and then produces power in the ORC Turbine (ORCT). LNG (state 1M), at ambient pressure and temperature of approximately -160 ºC, is first pumped to a higher pressure (state 2M) by a LNG pump (LNGP). In fact, the LNG fluid (state 2M) is gasified as a saturated natural gas (state 3M) by the first heat exchanger (H.E1), and then, the second heat exchanger (H.E2) is used to increase its temperature. After producing power in the LNG turbine (LNGT), the natural gas temperature drops significantly (state 5M). So, the third heat exchanger (H.E3) is used to increase the natural gas temperature for consumption (15 ºC). Meanwhile, temperature of the outlet water from H.E1 (state 3) decreases in the H.E3 and reaches the appropriate temperature for swimming and bathing (29 ºC).

2. 1. Energy and Exergy Analyses The mass flow rate balance and energy interactions across a control volume can be written as follows [19]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{2}$$

where, $\dot{m}$, h, $\dot{Q}$ and $\dot{W}$ are the mass flow rate, enthalpy, heat transfer and work, respectively.

The total exergy is the sum of the physical exergy, $\dot{E}_{ph}$, and chemical exergy, $\dot{E}_{ch}$, that can be defined as follows [20]:

$$\dot{E}_{tot} = \dot{E}_{ph} + \dot{E}_{ch} \tag{3}$$

where $\dot{E}_{ph}$ is obtained from following equation [20].

$$\dot{E}_{ph} = \dot{m}\left(h - h_0 - T_0\left(s - s_0\right)\right) \tag{4}$$

The fuel exergy is the sum of the product exergy, $\dot{E}_P$, and the destroyed exergy, $\dot{E}_D$, that can be defined as follows [20]:

$$\dot{E}_F = \dot{E}_P + \dot{E}_D \tag{5}$$

The thermal and exergy efficiencies can be calculated from Equations (6-7) [13,18].

$$\eta_{th} = \frac{\dot{W}_{\text{net}}}{\dot{m}_1\left(h_1 - h_0\right)} \tag{6}$$

$$\eta_{ex} = \frac{\dot{W}_{\text{net}} + \dot{E}_{6M}}{\dot{E}_1 + \dot{E}_{1M}} \tag{7}$$

where [13,18],

$$\dot{W}_{\text{net}} = \dot{W}_{\text{ORCT}} + \dot{W}_{\text{NGT}} - (\dot{W}_{\text{ORCP}} + \dot{W}_{\text{LNGP}}) \tag{8}$$

2. 2. Assumptions To simplify the energy and exergy analyses, the following assumptions are considered:

- Heat losses across the heat exchangers are negligible.
- Pressure drops of pipes are not considered.
- R123, R141b and R245fa are used as the ORC working fluid because of environmental sustainability, safety and thermodynamic properties.
- The ambient temperature and pressure, pool temperature, isentropic efficiencies of the turbines and pumps and pinch point temperature difference, LNGP output pressure, consumption gas pressure and H.E1 output temperature are assumed as 15 ºC, 101.3 kPa, 29 ºC, 85%, 90%, 3 ºC, 3000 kPa, 300 kPa, 40 ºC, respectively.
- Thermodynamic characteristics of Gaynarjeh hotspring are listed in Table 1.

2. 3. Optimization Method To optimize the cogeneration system from the energy point of view, the genetic algorithm is implemented by EES software. The optimization is performed to reach the maximum power generation. Also, the summary of research methodology in this study is illustrated in Figure 2.

2. 4. Validation The ORC simulation results are compared with Yari et al. [21], as shown in Figure 3. Also, for LNG system, thermodynamic results are compared with Mosaffa et al. [13], as Table 2 indicates. It can be seen that the obtained results have good accordance with previous studies.

3. RESULTS AND DISCUSSION

For the cogeneration cycle and according to the assumed thermodynamic condition for R245fa working fluid, the net output power, natural gas mass flow rate as

TABLE 1. Thermodynamic data of Gaynarjeh hotspring

Parameter	Value
$T\ (^{\circ}C)$	82
P (kPa)	101.3
$\dot{Q}(L/s)$	8
$h(kj/kg)$	343.4

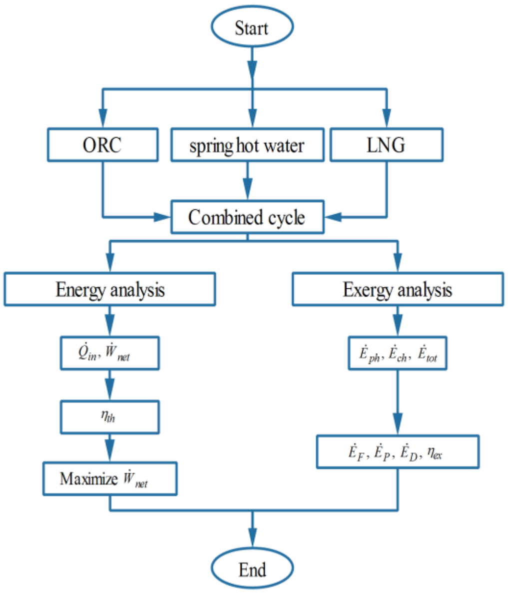

Figure 2. The summary research methodology

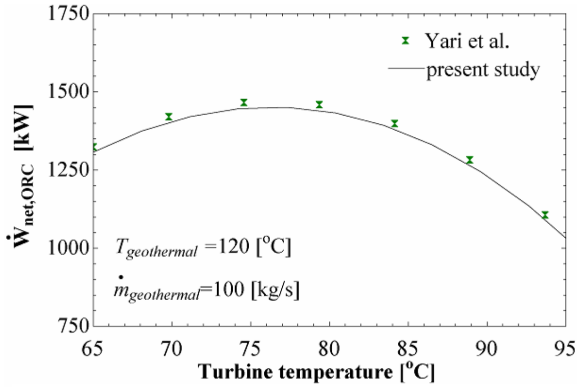

Figure 3. Verification of ORC with Yari et al [21] study

well as thermal and exergy efficiencies are calculated as 379.1 kW, 1.517 kg/s, 17.41 and 38.28%, respectively. Moreover, to explain the heat transfer process in the evaporator, the temperature-relative heat transfer (Q) diagram is depicted in Figure 4.

TABLE 2. Verification of LNG system with Mosaffa et al [13] study

	T (°C)		(kPa) P		(kJ/kg) h		s (kJ/kgK)	
State	**Persent study**	**[13]**	**Persent study**	**[13]**	**Persent study**	**[13]**	**Persent study**	**[13]**
1M	-161.5	-161.5	101.3	101.3	-910.9	-910.9	-6.677	-6.68
2M	-160.5	-160.5	3000	3000	-903.3	-903.3	-6.67	-6.67
3M	-95.87	-95.9	3000	3000	-371	-371	-3.339	-3.34
4M	65.29	65.3	3000	3000	68.36	68.36	-1.52	-1.52
5M	-59.8	-59.8	300	300	-187.6	-187.6	-1.298	-1.29
6M	25	25	300	300	-2.933	-2.94	-0.5697	-0.57

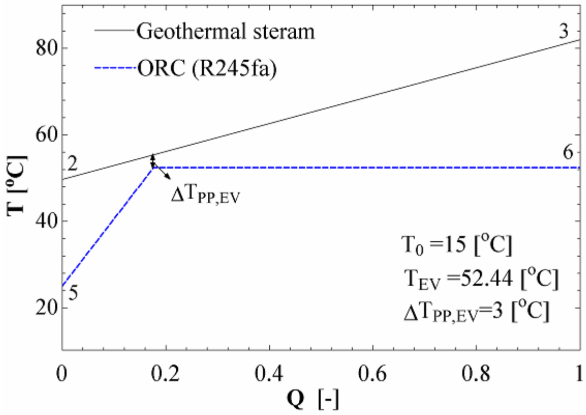

Figure 4. temperature-relative heat transfer process in the evaporator

3. 1. Parametric Study

A parametric study is implemented to assay the influences of the decision variables on the performance parameters of the system. The changes of net output power and thermal and exergy efficiencies are investigated. The influences of evaporator temperature, T_{EV}, for R123, R141b and R245fa are depicted in Figure 5. As shown this figure, R245fa has better performance compared to the other working fluids. Thus, R245fa is selected for further study.

Figure 6 demonstrates the variations of performance of the system with T_{EV}, which indicates that, the values of $\dot{W}_{net}$ and consequently, η_{th} and η_{ex}, which can be resulted from Equations (6)-(8), have maximum values at a similar T_{EV}. The trends of ORCT power generation and ORCP power consumption lead to the optimum values of performance parameters with T_{EV}. The optimum T_{EV} for maximizing the net power output (379 kW), thermal efficiency (17.4%) and exergy efficiency (38.25%) is obtained to be about 53°C in the cogeneration cycle.

The effects of the pinch point temperature difference of the evaporator, $\Delta T_{PP,EV}$, on the performance of the system, are depicted in Figure 7, where it can be observed that the performance parameters decrease with $\Delta T_{PP,EV}$. When $\Delta T_{PP,EV}$ increases, T_6 as well as h_6 decrease. Thus, the ORCT power generation and also the net output power as well as the thermal and exergy efficiencies of the cogeneration system decrease.

The variations of the performance parameters such as the net output power and the thermal and exergy efficiencies of the cogeneration cycle with LNGP pressure, P_{2M}, are illustrated in Figure 8. When P_{2M} increases, the NGT power generation and LNGP consumption power increase but NGT power generation dominates LNGP consumption power. Thus, the net output power, and consequently, the thermal and exergy efficiencies increase with P_{2M}. It is implied from Figure 8 that $\dot{W}_{net}$ rises from 245.1 to nearly 380 kW, η_{th}changes from 11.26 to nearly 17.4% and η_{ex}increases from 30.11 to nearly 38.28% by increasing P_{2M} from 1000 kPa to 3000 kPa.

Concerning Figure 9, maximum exergy destruction belongs to H.E.2 (486.5 kW) and H.E.1 (367.7 kW). Large amounts of exergy destruction for these two heat exchangers are because of the high-temperature gradient difference of cold and hot stream. The pumps have the lowest exergy destructions among the components. Also, Figure 10 illustrates the overall exergy balance and shows that 20.56 and 17.65% of the input exergy are converted to the power generation and produced natural gas exergy stream, respectively.

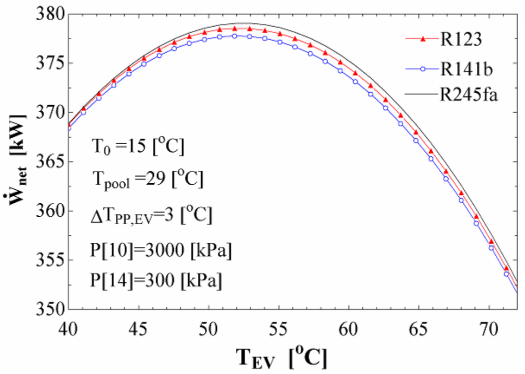

Figure 5. Effect of T_{EV} for various ORC fluids on the power generation

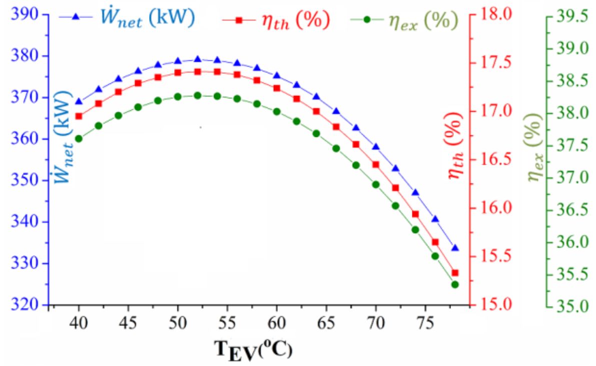

Figure 6. Effect of T_{EV} on the performance of system

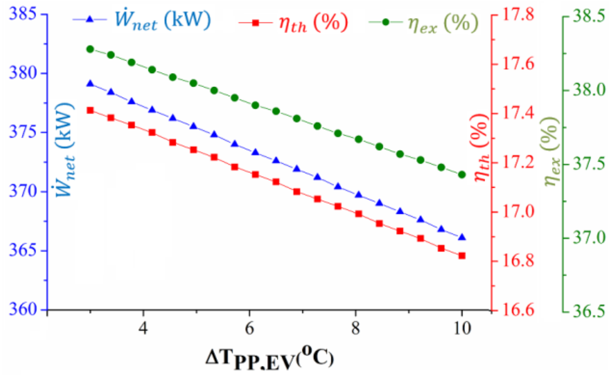

Figure 7. Effect of $\Delta T_{PP,EV}$ on the performance of system

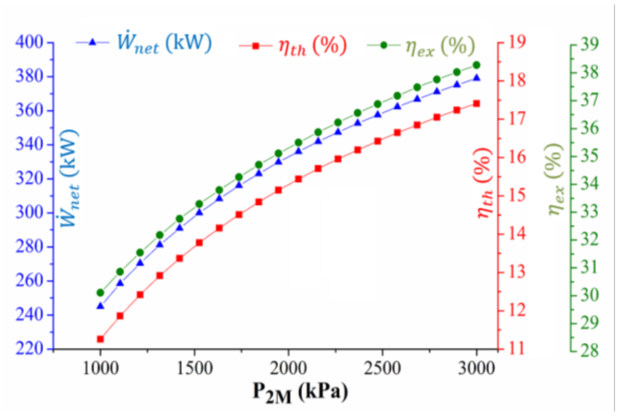

Figure 8. Effect of P_{2M} on the performance of system

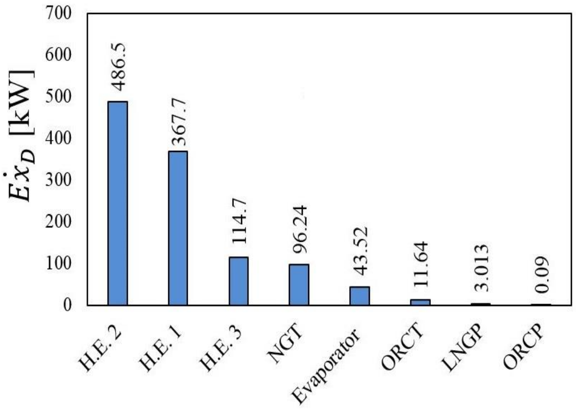

Figure 9. Exergy destruction rate for components

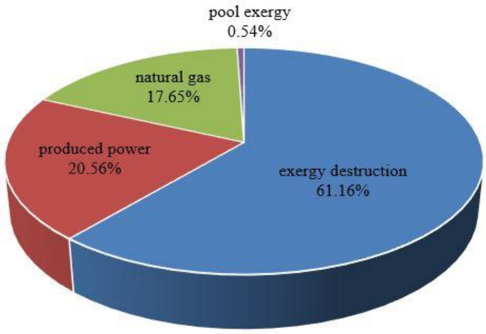

Figure 10. Overall exergy balance of the proposed system

3. 2. Optimization Results The optimization is performed to maximize the produced power. The results for the considered ORC fluids are listed in Table 3. The results show that R245fa has the best performance from the thermodynamic viewpoint because the system with R245fa produces more power and have the highest energy and exergy efficiencies. Also, Table 3 illustrates that for the cogeneration cycle utilizing Gaynarje hotspring energy, the net power generation, natural gas mass flow rate, exergy destruction rate and thermal and exergy efficiencies are obtained to be 524.9 kW, 1.352 kg/s, 837.5 kW, 24.11 and 48.99% for R245fa at the optimum conditions, respectively.

TABLE 3. Optimization results for proposed cycle

Decision variables/ Performance parameters	**Woeking fluid for ORC**		
	R123	**R141b**	**R245fa**
$T_{EV}\ ({}^{\circ}C)$	52.18	52	52.44
$\Delta T_{PP,EV}\ ({}^{\circ}C)$	3	3	3
$T_3\ ({}^{\circ}C)$	29	29	29
$\dot{W}_{net}\ (kW)$	524.3	523.6	524.9
$\dot{m}_{NG}\ (kg/s)$	1.353	1.354	1.352
$\dot{E}_{D,tot}\ (kW)$	838.5	840	837.5
$\eta_{th}\ (\%)$	24.09	24.05	24.11
$\eta_{ex}\ (\%)$	48.94	48.88	48.99

4. CONCLUSIONS

Because of the Gaynarje spring high temperature, 82 °C, it is not suitable for swimming and bathing usage. Accordingly, a new cogeneration cycle from this hotspring output water is proposed based on ORC and LNG cold. In addition to lowering the spring temperature to the appropriate swimming temperature, the hot water is used for power and natural gas production, in the suggested cycle. Mass, energy and exergy equations are developed for the components and the performance parameters are calculated considering several working fluids for the ORC. The important results of the study are listed here:

- R245fa as an ORC working fluid has the best performance from the thermodynamic point of view.
- The maximum exergy destruction belongs to the H.E.2 and H.E.1.
- At optimum condition from the energy viewpoint and for R245fa working fluid, the net power generation, natural gas mass flow rate, exergy destruction rate and thermal and exergy efficiencies are obtained to be 524.9 kW, 1.352 kg/s, 837.5 kW, 24.11% and 48.99%, respectively.
- It can be seen from the parametric study that the performance parameters of the system have optimum values with respect to the evaporator temperature.
- The produced power and energy and exergy efficiencies increase with LNG turbine inlet pressure and decrease with the pinch point temperature difference in the evaporator.

The results of the present work can be used as a basis for the exergoeconomic assessment of the proposed system.

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Persian Abstract

چکیده

آب گرم قینرجه (به معنای بسیار داغ) به عنوان یکی از گرمترین چشمه‌های آب گرم دنیا در منطقه مشگین شهر و در شمال غرب ایران قرار گرفته است. استفاده از این آب معدنی برای شنا و استحمام، با توجه به دمای ۸۲ درجه سلسیوس این چشمه، مناسب نمی‌باشد. در این بررسی علاوه بر کاهش دمای این چشمه آب گرم به دمای مناسب شنا (۲۹ درجه‌ی سلسیوس)، با استفاده از یک چرخه‌ی پیشنهادی بر پایه چرخه رانکین آلی و انرژی گاز طبیعی مایع شده، از گرمای آب چشمه برای تامین توان الکتریکی و گاز طبیعی استفاده شده است. همچنین این آرایش نسبت به پارامترهای مهم عملکردی مورد مطالعه قرار گرفته و سپس مورد بهینه‌سازی قرار گرفته است. بدین منظور روابط جرم، انرژی و اگزرژی برای اجزای سیستم و نیز کل سیستم توسعه داده شده و پارامترهای عملکردی محاسبه شده‌اند. برای دستیابی به بهترین نتایج، سیالات کاری متعددی برای چرخه رانکین آلی در نظر گرفته شده است. طبق نتایج حاصله سیال R245fa به عنوان سیال عامل چرخه رانکین آلی بهترین عملکرد ترمودینامکی را داشته و همچنین در حالت بهینه برای آرایش پیشنهادی، توان خالص تولیدی، تولید گاز طبیعی، بازده حرارتی و بازده اگزرژی به ترتیب ۵۲٤/۹ کیلووات، ۱/۳۵۲ کیلوگرم بر ثانیه، ۲٤/۱۱ درصد و ٤۸/۹۹ درصد حاصل شده است. همچنین مطالعه پارامتری نشان داد که پارامترهای عملکردی سیستم نسبت به دمای اواپراتور مقادیر بهینه دارند.