Transient Simulation and Exergy Analysis of Heat-Pump Systems Integrated with Solar Compound Parabolic Collector

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ABSTRACT: *In high exergy demand companies like piping companies, using renewable energies can be very useful in Manning the needed energy. Exergy analysis in thermal energy systems is very important, considering the need to determine the location and magnitude of the inefficiency of the system equipment. Utilizing annual meteorological data for Dezful, located in southwest Iran, this study considered the inefficiency of the solar water heating system. As an innovation, a complete analysis of the inefficiency of the equipment of the solar hot water production cycle was considered and the methods of reducing the inefficiency of the equipment were assessed. Energy consumption quality was calculated based on two parameters of exergy efficiency and exergy destruction using the coding capability of MATLAB software, after embedding the modeling in Aspen HYSYS software. While solar collector with 15701.8 kW and Pump1 with 0.51 kW had the highest and lowest exergy destruction, Heat Exchanger 2 with 99.99% and Pump1 with 75.51% had the highest and lowest exergy efficiency. Among the rotating equipment that consumes electricity, Compressor 2 had the most exgegy degradation with 223.1 kW. Also, the results of investigating the effect of ambient temperature showed that the solar collector had the highest and lowest exergy destruction in the month of JAN with 16125.7 kilowatts and in the month of July with 14927.6 kilowatts, and compressor 2 also had the highest exergy destruction in the month of Jan with 216.11 kilowatts and in the month of July with 235.76 kilowatts. and had the least exergy destruction.*

KEYWORDS: *Renewable energy, Solar energy, Solar collector, Exergy analysis, Exergy destruction.*

INTRODUCTION

Exergy analysis evaluates the efficient use of solar energy in solar heat pump systems. By determining the sources and magnitude of the irreversible energy, exergy analysis can be used to improve the efficiency of a heat pump system [1, 2]. This method has proven to be a powerful tool for simulating the thermodynamic analysis of energy

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systems. In other words, it has been widely used in designing, simulating, and evaluating the performance of energy systems. The maximum work that can ideally be produced for a certain amount of energy under environmental conditions under optimal conditions is exergy. Therefore, this method is a useful way to design the operation of many industrial processes[3-6]. As it is known, exergy is the maximum useful work that can be obtained from energy systems under environmental conditions. Because exergy is the optimal use of energy taking into account the influencing environmental conditions, exergy analysis of industrial systems is a useful method for designing many industrial processes. In this sense, in the heat pump and solar collector system components, the dynamic exergy analysis of the equipment with the influence of environmental conditions can also be recognized by simulation.

Research and development continue to improve the performance of heat transfer equipment such as evaporators, condensers, and compressors. The analysis of the equipment used in the industry is still based on the first law of thermodynamics. The analysis causes the identification of inefficiencies and their limitations, and the decision for further improvement.

Many researchers have examined exergy analysis methods, applied them to many renewable energy systems, and different energy applications, and opened distinct windows to focus on exergy analysis and modeling studies[7-10]. *Dinser* [10] have been applied energy and exergy analyses for several years in different areas of Saudi Arabia. Based on his research, the relationship between energy and exergy of different factors, such as environmental, sustainable development, and policy was investigated.

In recent years, theoretical analysis based on the concept of exergy and experimental studies for heat pump systems has been reported. *Ding et al.* [11] In a study, it studied an improved air source (ASHP) heat pump and introduced a new subcooling system with supplemental injections using a scroll compressor that can effectively solve problems. *Ozgener* and *Hepbasli* [12] exergy analyzed the performance of a greenhouse system using a solar source heat pump using renewable energy sources (SAGSHP). They investigated the performance characteristics of the system as the main effective indicator. *Ayhan* and *Kaygusuz* [13] experimental efficiency of solar-assisted heat pump systems for home heating was experimentally investigated. Exegetic efficiencies are calculated using experimental data and comparisons are made between different systems. *Mehrpoya et al.* [14] investigated the optimal design of a combined solar collector and geothermal heat pump system. The system was simultaneously analyzed to optimize it from a technical and economic point of view. From technical and economic points of view, the optimal conditions were calculated, and to create a balance between economic and technical issues, the final optimal design was carried out. *Gang Pei et al.* [15] presented the operation of a multipurpose home heat pump system and discussed the principles of operation and the basic features of these systems. The results show that the new system can save energy through multiple tasks and can operate stably under long-term performance in areas with mild winter temperatures. They are a multipurpose home heat pump system that can provide much better energy efficiency and higher utilization of equipment, causing less heat pollution than conventional heat pump water heaters and air conditioners. *Dikici*, *Akbulut* [16] experimental efficiency of solar-assisted heat pump systems for home heating was experimentally investigated. Exegetic efficiencies are calculated using experimental data and comparisons are made between different systems. *Torres Reyes et al.* [17] studied the theoretical and experimental exergy analysis of a solar-assisted heat pump for air heating. To determine the exergetic efficiency, the irreversibility of the whole system and the irreversibility of the components were tested. And discussed the optimal evaporation temperature as a function of a parameter that includes environmental conditions and the overall heat transfer coefficient. Contract. *Badescu* [18] studied the heat pump heating system as the main source of solar radiant energy. Both the first rule and the second rule were used to analyze the performance of the heat pump. The analysis of the second law emphasized that most exergy losses occur during compression and compaction. The results show that the photovoltaic array can provide all the energy needed to move the heat pump compressor.

Hepbasli and *Akdemir* [19] analyzed the energy and exergy of a GSHP system with a ground heat exchanger. They also examined the transfer of exergy between components and consumption in each component of the system.

Li et al. [20, 21], a pilot set of solar expansion water heat pumps with direct expansion (DX-SAHPWH) was studied. They evaluated the system through exergy analysis for each component of the DX-SAHPWH system. Most exergy losses occur in the compressor, followed by the collector/evaporator, condenser, and expansion valve. They also calculated the exergy loss coefficient of each component and the exergy efficiency of the entire DX-SAHPWH system. *Hepbasli* [22], studied and presented the energy and exergy analysis of a GSHP system with a ground-based heat exchanger. The integrated ground source heat pump systems with exergetic modeling evaluated the performance of a domestic hot water tank and applied the model in one system. Exergy transfer between components and consumption in each component of the GSHP system was determined by the average of the measured parameters obtained from the experimental results. *Li et al.* [23], analytical and experimental studies were performed on the direct heat-assisted solar heat pump (DX-SAHP) water heating system and a simulation model was developed to predict the approximate long-term thermal performance of the system and the effect of various parameters such as solar radiation, and ambient temperature. Collector level, storage volume, and compressor speed are checked on the thermal performance of the direct-expansion solar-assisted heat pumps (DX-SAHP) system. The results show that the most exergy losses occur in the compressor and collector/evaporator, followed by the condenser and expansion valve, respectively.

The use of fossil fuels has a negative effect on the environment, and this issue increases the importance of using renewable resources[24, 25]. Solar source industrial heat pump systems have been proposed for hot water production. Solar energy systems and the heat pumps connected to them are promising tools for reducing the consumption of non-renewable energy sources and reducing the cost of energy delivered to produce hot water for industries and similar applications. Exergy analysis is performed here to improve the performance of a solar source heat pump cycle (compound parabolic concentrator solar collector) to produce hot water. This analysis of ambient temperature is based on the environmental conditions of Dezful for all months of the year. To lead by identifying inefficient parts of the system and optimal operating conditions. Although there are numerous experimental and theoretical studies on the process of solar heat pumps and solar collectors, few articles have been presented on the exergy analysis of solar heat pump industrial heat pump systems for hot water production. Therefore equipment inefficiency solar assisted heat pump was mentioned for this research.

ANALYSIS METHODOLOGY

Data analysis was carried out using Aspen HYSYS software, which is one of the most powerful and accurate engineering software for modeling refinery, petrochemical, and electrolytic processes. Due to this software's accurate and powerful design, which is based on the property packages associated with different materials and their equations of state, this software has been able to produce models that represent processes very realistically. Using its comprehensive library and the most accurate methods, it performs complex and long engineering calculations in the shortest time possible and provides them to users. MATLAB software is also used in many industries and is widely used in basically any job and profession that requires accurate data analysis. Considering that accurate data is one of the most important and strategic pillars of an organization in the present era, therefore, data analysis and accurate mathematical and statistical calculations with MATLAB software are of great importance. One of the properties of this software is extracting input data from another software library to perform calculations accordingly. Therefore, more accurate exergy calculations can be achieved by extracting process and thermodynamic data from Aspen HYSYS software and performing analysis in MATLAB software.

Process description

A heat pump assisted by indirect solar radiation is used in the study. As an alternative to natural gas, water, or electric heaters, the system is used for water heating applications. The solar collector and the heat pump together form the water heating system of a solar heat pump.

Fig. 1: Solar hot water production system of Dezful Industrial Town No. 2.

The collector also serves as an evaporator. A heat pump and collector integrated this way eliminates the need for heat exchangers in systems that use water-based collectors, and using a refrigerant as a working fluid for the heat pump and collector allows the collector to be cooled quickly. The solar energy collection collector operates at a low temperature, but the heat pump operates at a high temperature, increasing its performance compared to an air source heat pump (ASHP) [26]. Figure 1 shows the location CPC arrangement in the Dezful Industrial Town No. 2. Here the collector collects solar energy and the heat collected from the sun is transferred to a secondary fluid. The refrigerant inside the heat pump cycle passes through the evaporator and evaporates. Evaporated refrigerant enters the compressor and causes pressure and temperature to rise. The refrigerant then enters the condenser and loses its heat. Lowering the temperature causes the refrigerant to evaporate and liquefy. The refrigerant is then directed to the expansion valve to lower its temperature after the expansion process. The heat in the condenser is transferred to another fluid and it transfers its heat to it and the fluid heats up. R-134a, a refrigerant with low boiling points is used in Fig. 2 to schematically represent the cycle. A typical vapor-compression refrigeration cycle consists of four major parts: an expansion valve, evaporator, compressor, and condenser. The collector is in direct sunlight. The sun's energy is absorbed by the liquid refrigerant as it collides with the steel that transports it. In heat pumps, the evaporation of the hot working fluid in the heat pump evaporator converts the constant pressure of the subcooled liquid into saturated vapor; consequently, steps (1-4) involve the transfer of heat from the working fluid to the heat pump working fluid.

Using the evaporator and condenser pressures, process (2-3) compresses the refrigerant. The refrigerant is then taken out of the heat and condensed under a constant pressure of (3–4) to become a saturated liquid state. During this process, latent heat from condensation is transferred from the condenser to the water that is circulating. Relief valve expansion results in a mixture of liquid and vapor when the refrigerant is forced through it [27]. Heat pumps have long been used in sectors like manufacturing, refrigeration, and industrial applications [28]. They are used in many industrial processes, as well as for heating and cooling water, refrigeration, and home and business heating. When it comes to producing heat, heat pumps compete with fossil boilers and direct electric heating [29, 30].

All of the aforementioned information is provided as input with regard to the location where this equipment will be installed. The collector temperature is taken into account during a particular time of the day, and a set of points are chosen for the purpose of calculating enthalpy values. Compressor-absorbed solar energy and additional energy average monthly instantaneous values are calculated using compressors, collectors, and thermal modules. The values of these parameters are integrated over one month, then over all months, in order to obtain annual values.

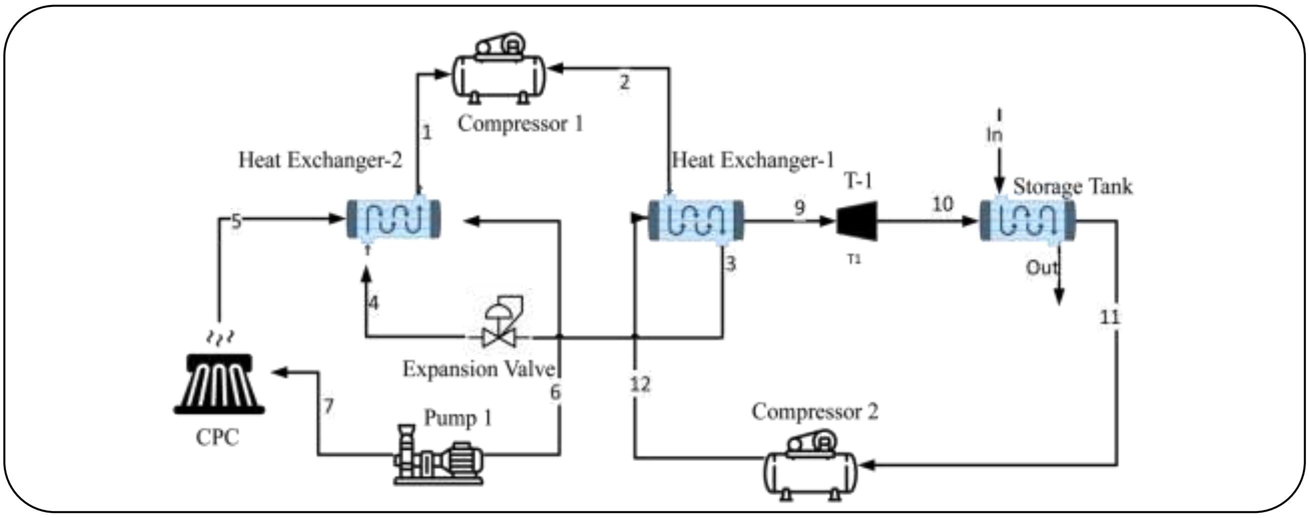

Fig. 2: Process status of the hot water production system of the studied company.

Fig. 2 shows the current condition of the heat pump for high temperatures and solar hot water production system for Dezful Industrial Town No. 2. The first part of this system consists of a solar compound parabolic concentrator (CPC), the second part is a heat pump, and the third part is a storage tank. The CPC receives energy from solar radiation, and the working fluid heats the collector. This fluid is pumped into the heat exchanger (evaporator) in order to transfer heat from the heat pump to the CPC working fluid. The four main parts of a vapor compression heat pump are the condenser, the compressor, the evaporator, and the expansion valve. The water enters the storage and exits after being heated, as shown in this diagram. Aspen HYSYS software has been used for process analysis with the Peng-Robinson equation of state. Additionally, table 1 displays the operational situation.

Exergy analysis

This article focuses on combining the two laws of thermodynamics described in the exergy analysis concept. To analyze the results, the following hypotheses are considered in thermodynamic relations.

a. According to the reference (dead) mode, the ambient temperature of the system is 20°C, and the pressure is 101.325 kPa.

b. The system works in a steady state.

c. There are negligible changes in kinetic and gravitational conditions in energy equilibrium and exergy.

d. The refrigerant (water) at the condenser outlet and the evaporator at the heat pump is saturated.

e. Pressure drop in all heat exchangers and pipelines is ignored.

Exergy is a thermodynamic measure of the energy quality and determines the equipment's deviation from the environmental reference state [27, 31-33]. In real processes, exergy is consumed or destroyed by irreversibility. This method can detect energy quality and prevent opportunities to use wasting energy. The analysis shows the most inefficient equipment and indicates where energy is being lost in operating conditions [34-38]. To perform energy analysis, it is crucial to determine the ambient conditions. The main purpose of exergy analysis is to determine the optimal state of energy consumption taking into account environmental and operational conditions [39-42]. This analysis identifies the most inefficient equipment and shows the number of destruction opportunities for the energy use of this equipment under different environmental conditions, which requires clear environmental conditions [36, 43, 44]. Determining the characteristics of the reference environment is very important in performing system evaluation [45-47]. According to the information collected from official sources, the average reference temperature and reference pressure of Dezful city (construction site of the Dezful Industrial Town No. 2) are considered to be 22 °C and 101.325 kPa, respectively [10, 48]. Therefore, it can be concluded that exergy analysis is a fundamental method to better identify the location, causes, and extent

Table 1: Process information of solar hot water production system flows of Dezful Industrial Town No. 2

Stream number	Temperature (ºC)	Pressure (kPa)	Molar Flow (kgmole/h)
1	275	150	597
2	330	400	597
3	89	400	597
4	89	150	597
5	275	90	597
6	90	90	597
7	90	90	597
8	90	150	597
9	330	50	1993
10	316	30	1993
11	40	30	1993
12	54	50	1993
13	54	50	1993
In	25	100	4432
Out	99.6	100	4432

of thermodynamic inefficiency of a process [49]. This analysis is a suitable method to evaluate the performance of chemical processes [48, 50].

The governing equations

According to Equation (1), in general, the exergy of any flow is divided into main four parts: kinetic ($\dot{E}x_{ke}$), potential ($\dot{E}x_{po}$), chemical ($\dot{E}x_{ch}$), and physical ($\dot{E}x_{ch}$) [49, 51, 52]. When the system is considered stationary in the environment, potential and kinetic exergy can be avoided [37, 53-55]. Therefore, the exergy value of each flow can be calculated according to Equation (2) [56-58]:

$$\dot{\mathrm{E}}\mathrm{x} = \dot{\mathrm{E}}\mathrm{x}_{\mathrm{po}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{ke}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{ph}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{ch}} \tag{1}$$

$$\dot{\mathrm{E}}\mathrm{x} = \dot{\mathrm{E}}\mathrm{x}_{\mathrm{ph}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{ch}} \tag{2}$$

Physical exergy represents the amount of work that can be achieved when a system moves from its initial state to a state of equilibrium with the environment in Eq. (3) [59, 60]. In chemistry, exergy is the amount of work that can be generated if the system is transferred from a dead state to a dead state in thermal and mechanical equilibrium with the environment [61, 62]. The physicochemical exergy of the flow is expressed according to Equations (3) and (4) [63]:

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{ph}} = \dot{\mathrm{m}}[(\mathrm{h} - \mathrm{h}_0) - (\mathrm{s} - \mathrm{s}_0)] \tag{3}$$

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{ch}} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{y}_\mathrm{i} \mathrm{e}_\mathrm{i}^0 + \mathrm{G} - \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{y}_\mathrm{i} \mathrm{G}_\mathrm{i} \tag{4}$$

To understand exergy analysis, it is important to understand the environment and the dead state employed during these calculations. The temperature, pressure, and chemical composition are commonly used to determine the dead state. The physicochemical exergy of the material flow is calculated using the equations below [64].

Where e_i^o, s and h, represent the standard chemical exergy of the components of flow, and specific enthalpy and, specific entropy respectively [65].

In the above equations, the zero indexes represent the environmental conditions. In equation (3) $\dot{m}, T_0, s_0, h_0$ are the mass flow rate, and reference ambient temperature, the specific enthalpy, specific entropy. Also, in Eq.(4) *Gi* is Gibbs free energy, and e_i^0 is the standard chemical exergy [66]. The calculation of the flow exergy is shown in Fig. 2. After obtaining these parameters, the exergy destruction and efficiency should be investigated and

Table 2: Results of exergy flow of solar hot water system of Dezful Industrial Town No. 2.

Stream number	Physical exergy(kW)	Chemical exergy(kW)	Total exergy(kW)
1	8920.88	45569	54490
2	9571.53	45569	55141
3	424.92	45569	45994
4	419.92	45569	45989
5	8761.70	45569	54331
6	255.27	45389	45825
7	435.27	45569	46005
8	436.86	45569	46006
9	8322.16	359094	367416
10	7031.52	359094	366125
11	416.98	359094	358677
12	343.67	359094	359437
13	343.69	359094	359437
In	0.03	297705	297704
out	4020.79	297705	301725

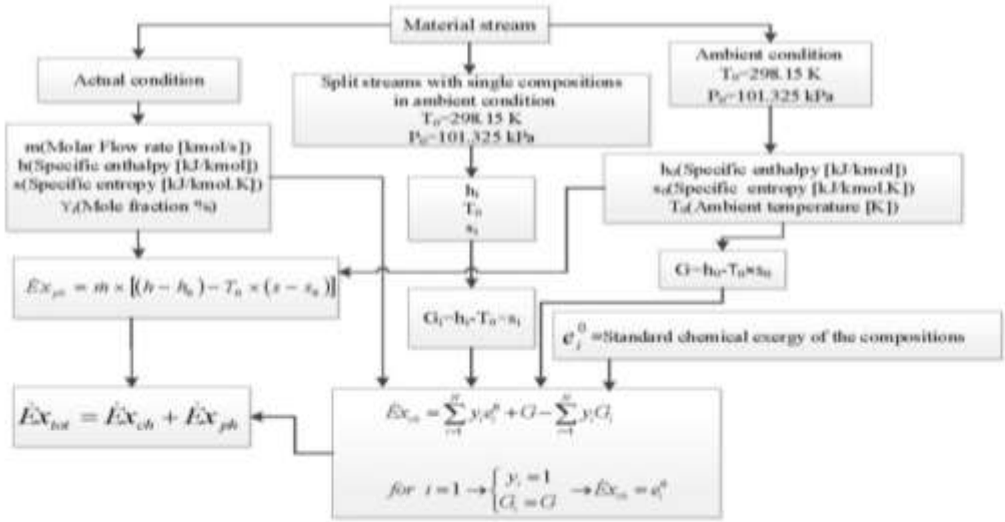

Fig. 3: Flowchart of calculation of the stream's exergy flow rate.

discussed in the analysis based on Equations (5) and (6). Equipment exergy should be defined for kth [51]. These basic parameters are investigated in order to equip *kth* [10].

$$\dot{E}x_D = \dot{E}x_F - \dot{E}x_P \tag{5}$$

$$\varepsilon = \frac{\dot{E}x_P}{\dot{E}x_F} = 1 - \frac{\dot{E}x_D}{\dot{E}x_F} \tag{6}$$

In the above relations, product, destruction, and fuel are shown using P, D, and F indices, respectively. The flowchart of exergy flow is plotted in Fig. 3.

RESULTS AND DISCUSSION

The results of physical, chemical, and total exergy resulting from the analysis of exergy flow in MATLAB software are presented in Table 2. Table 3 displays the equipment's efficiency and exergy destruction. The results of the simulation output from the Aspen HYSYS software according to the influencing conditions of the Aspen HYSYS

Table 3: Exergy results of the main equipment of Dezful Industrial Town No. 2 Production System.

Equipment number	Exergy destruction(kW)	Exergy efficiency (%)
Compressor 1	90.82	87.75
Compressor 2	223.1	77.33
Pump	0.51	75.51
Storage tank	3427.68	86.25
Heat Exchanger 1	1168.14	85.64
Heat Exchanger 2	5.47	99.99
Collector	15701.8	99.11
Expansion Valve	5.00	99.99
Expander	105.05	91.86

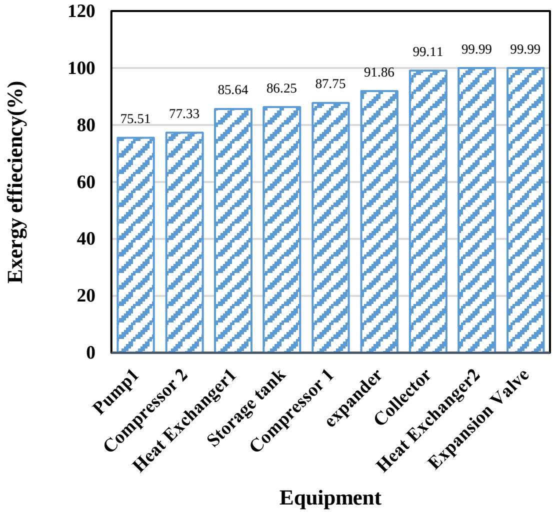

Fig. 4: Exergy efficiency of all equipment.

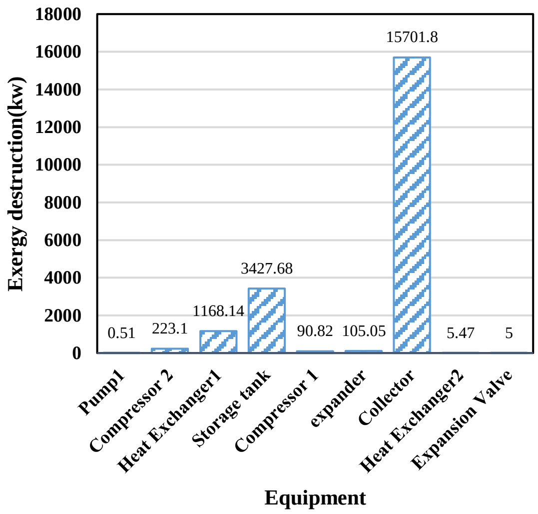

Fig. 5: Exergy destruction of all equipment.

software are given in Table 3. Based on the comparison of equipment exergy, the most exergy destruction is in the solar collector. Figures 4 and 5 show the detailed analysis of exergy destruction and solar hot water production efficiency in Dezful, Industrial Town No. 2 according to the simulation results in Aspen HYSYS software. Fig. 4 also shows the amount of equipment destroyed.

In order to analyze the effect of equipment performance on exergy destruction, the technical limitations of the equipment with the most exergy destruction have been reviewed. The operating and ideal conditions of these two pieces of equipment can be observed in Table 4.

Fig.4 shows the main parameters vary within the isentropic efficiency. As can be seen, exergy destruction is reduced and exergy efficiency is increased. It concludes that more attention should be paid to improving this equipment based on exergy concepts.

ANALYSIS OF THE EFFECT OF AMBIENT TEMPERATURE

The ambient temperature of the reference environment can affect the performance of a system [67]. Here, the local air temperature is measured for 12 months of the year and is given in Table 5. The effect of temperature on the heat pump performance and exergy of the solar-assisted heat pump system has been investigated by applying the influencing factors in objectification. The annual temperature of Dezful city is given in Table 5 and Fig. 6.

Table 4: Assumptions for calculating exergy destruction in both operational and ideal modes for compressor and heat exchanger [51, 52].

Components	Real conditions	Ideal conditions
Compressor	$\eta_{is} = 75\%$	$\eta_{is} = 100\%$
Heat Exchanger	$\Delta T_{min} = real$	$\Delta T_{min} = 0\ K$
	$\Delta P = real$	$\Delta P = 0$

Fig. 5: Annual temperature in Dezful [33].

Month	T_{max}	T_{min}	T_{ave}
Jan	16	7.5	11.75
Feb	20.4	10.5	15.45
Mar	27.8	13.8	20.8
Apr	32.7	19.2	25.95
May	37.6	27.3	32.45
Jun	39.9	35.7	37.8
Jul	44	37	40.5
Aug	40.2	36	38.1
Sep	40	30.5	35.25
Oct	33.9	22	27.95
Nov	28.1	17.3	22.7
Dec	20	10.9	15.45

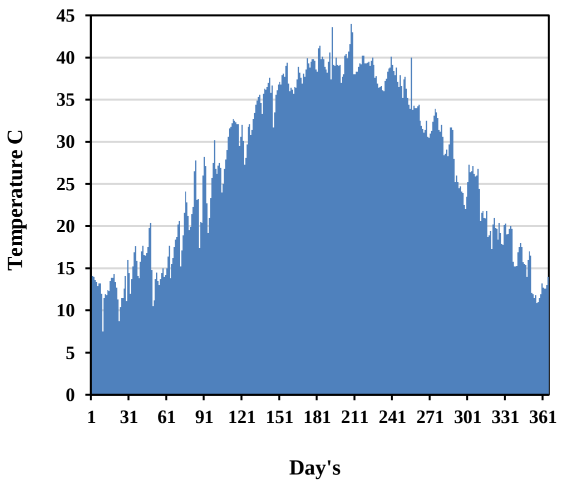

Fig. 6: Annual temperature in Dezful [33].

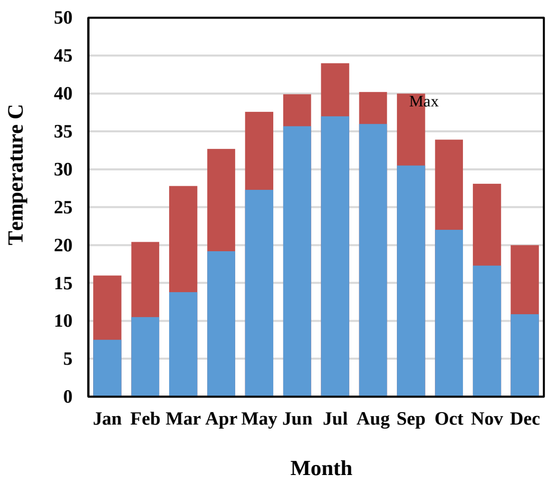

Fig. 7: Minimum and maximum temperatures, various in 2021 [33].

Here, Fig. 7 demonstrates the results of temperature studies, (local temperature changes in 12 months effects on exergy destruction and efficiency).

The maximum local temperature for all months of 2020 is shown in Figure 8.

The effective conditions in the simulation were applied for 12 months of the year, and the amount of energy destroyed by all equipment is given in Fig. 9.

The amount of exergy destruction of equipment in 12 months of 2020 was according to the simulation results, the exergy degradation changes of the compressor-2 and solar collector have been shown in all months of 2020. According to Figs. 10 and 11, the highest exergy destruction of solar collectors and compressors-2 are in January and July.

For November and July, the compressor-2 efficiency and exegetic parameter were evaluated. In fact, in the analysis

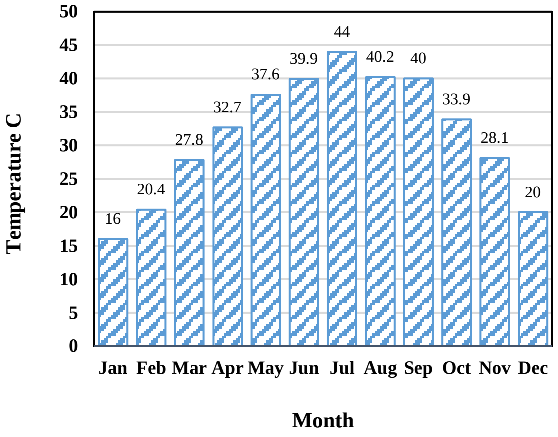

Fig. 8: Annual max temperature in Dezful [33].

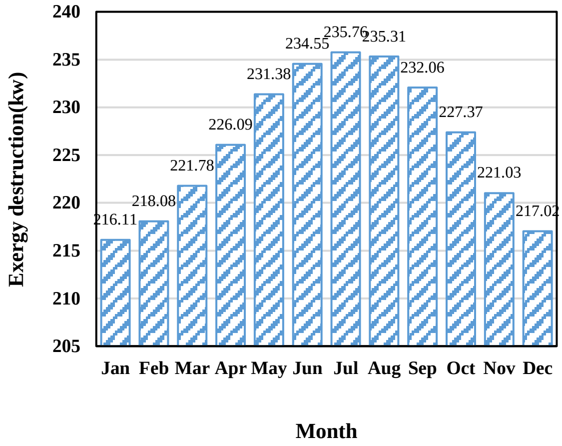

Fig. 10: Exergy destruction variation of compressor-2 in 12 months of 2020.

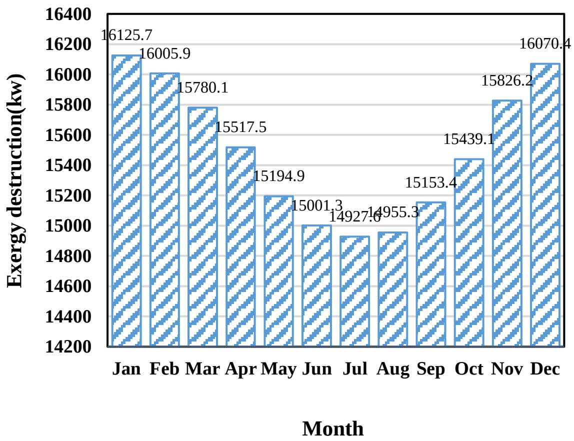

Fig. 9: Exergy destruction variation of collector compressor in 12 months of 2021.

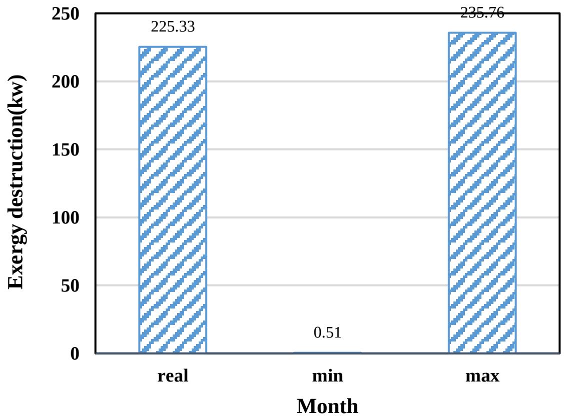

Fig. 11: Maximum and minimum amount of equipment destruction of compressor-2 based on two criteria of variable temperature throughout the year and isotropic efficiency of the equipment.

min and max exergy destruction in 12 months and isentropic efficiency were analyzed. According to Figure 11, the real amount of exergy destruction based on 75% efficiency and 22 ° C local temperature is equal to 220 kW. Now, for November and 100% efficiency, this amount of destruction will be reduced to up 0.02%. Also, if this amount of destruction is performed for July and 75% of efficiency, the amount of exergy destruction is 235.76 kW. This shows the effect of these two parameters on the exergy destruction of this equipment.

CONCLUSIONS

This paper analyzes the exergy of a solar-assisted heat pump. The effect of ambient temperature and daily reference temperature was investigated. Exergy analysis was also performed, and the exergetic efficiency of the equipment and ambient temperature were evaluated. This method was used to gain a better understanding of the locations, causes, and strategies to improve the inefficiency of the solar hot water production system equipment of the Dezful Industrial Town No. 2. the exergy analysis found that the solar collector was the source of the most exergy destruction (220 kW). While the annual temperature ranges from 3 to 48 degrees, the exergy destruction of the equipment varies between 0.51 and 235.76 kW. Also, rotary results show that with increasing the isentropic efficiency of this equipment, exergy destruction decreases and exergy efficiency rises. Improving compressor performance significantly reduces exergy destruction, which indicates that improving the performance of this equipment improves the overall energy efficiency of the equipment.

Nomenclature

$\dot{E}x$	Exergy rate, kW
e_i^0	Standard chemical exergy
$\dot{m}$	Mass flow rate, kg/s
E	Special energy, kJ/kgmol
E	Specific exergy, kJ/kg
Gi	Gibbs free energy, kJ/kgmol
h	Specific enthalpy, kJ/kg
Q	Heat transfer, kJ
T	Temperature, C
W	Work, kW
s	Entropy, kJ/kg K
ε	Exergy efficiency

Subscript

D	Exergy destruction
P	The product
F	Fuel
0	Dead state
in	Entrance
out	Output
po	Potential
Ph	Physical
ch	Chemical
ke	Kinetic
tot	General
F	Fuel
P	The product
ex	Exergy

Symbols

HE	Heat Exchanger
Evap	Evaporator
Cond	Condenser
Comp	Compressor
Pum	Pump
Coll	Collector
SHP	Air source heat pump
CPC	Compound parabolic concentrator

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REFERENCES

[1] Hoseinzadeh S., Garcia D.A., Techno-economic Assessment of Hybrid Energy Flexibility Systems for Islands' Decarbonization: A Case Study in Italy, *Sustainable Energy Technologies and Assessments*, **51**: 101929 (2022).

[2] Gilani H.A., Hoseinzadeh S., Esmaeilion F., Memon S., Garcia D.A., Assad M.E.H., A Solar Thermal Driven ORC-VFR System Employed in Subtropical Mediterranean Climatic Building, *Energy*, **250**: 123819 (2022).

[3] Jafari S., Sohani A., Hoseinzadeh S., Pourfayaz F., The 3E Optimal Location Assessment of Flat-Plate Solar Collectors for Domestic Applications in Iran, *Energies*, **15(10)**: 3589 (2022).

[4] Bazregari M.J., Norouzi N., Gholinejad M., Khavasi E., Fani M., A 2E Analysis and Optimization of a Hybrid Solar Humidification-Dehumidification Water Desalination System and Solar Water Heater, *Iranian Journal of Chemistry and Chemical Engineering (IJCCE)*, (2021) [in Press].

[5] Norouzi N., Talebi S., Fabi M., Khajehpour H., Heavy Oil Thermal Conversion and Refinement to The Green Petroleum: A Petrochemical Refinement Plant Using the Sustainable Formic Acid for the Process, *Biointerface Res. Appl. Chem*,**.** **10(5)**: 6088-6100 (2020).

[6] Norouzi N., Kalantari G., Talebi S., Combination of Renewable Energy in the Refinery, with Carbon Emissions Approach, *Biointerface Res. Appl. Chem*, **10(4)**: 5780-5786 (2020).

[7] Khajehpour H., Norouzi N., Bashash Jafarabadi Z., Valizadeh G., Hemmati M.H., Energy, Exergy, and Exergoeconomic (3E) Analysis of Gas Liquefaction and Gas Associated Liquids Recovery Co-Process Based on the Mixed Fluid Cascade Refrigeration Systems, *Iranian Journal of Chemistry and Chemical Engineering (IJCCE)*, **41(4):** 1391-1410 (2022).

[8] Ajam M., Mohammadiun H., Dibaee Bonab M.H., Mohammadiun M., Energy, Exergy and Economic Analyses of a Combined Heat and Power Generation Systems with a Gas Turbine and a Horizontal Axis Wind Turbine, *Iranian Journal of Chemistry and Chemical Engineering (IJCCE)*, **41(6):** 2100-2120 (2022).

[9] Norouzi N., Choupanpiesheh S., Talebi S., Khajehpour H., Exergoenvironmental and Exergoeconomic Modelling and Assessment in the Complex Energy Systems, *Iranian Journal of Chemistry and Chemical Engineering (IJCCE)*, **41(3):** 989-1002 (2022).

[10] Dincer I., Hussain M., Al-Zaharnah I., Energy and Exergy Use in Public and Private Sector of Saudi Arabia, *Energy Policy*, **32(1)4**:1615-1624 (2004).

[11] Ding Y., Chai Q., G.Ma, Jiang Y., Experimental Study of an Improved Air Source Heat Pump, *Energy Conversion and Management*, **45(15-16)**: 2393-2403 (2004).

[12] Ozgener O., Hepbasli A., Experimental Performance Analysis of a Solar Assisted Ground-Source Heat Pump Greenhouse Heating System, *Energy and Buildings*, **37(1)**: 101-110 (2005).

[13] Kaygusuz K., Ayhan T., Exergy Analysis of Solar-Assisted Heat-Pump Systems for Domestic Heating, *Energy*, **18(10)**: 1077-1085 (1993).

[14] Mehrpooya M., Hemmatabady H., Ahmadi M.H., Optimization of Performance of Combined Solar Collector-Geothermal Heat Pump Systems to Supply Thermal Load Needed for Heating Greenhouses, *Energy Conversion and Management*, **97**: 382-392 (2015).

[15] Ji J., Pei G., Chow T., He W., Zhang A., Dong J., Yi H., Performance of Multi-Functional Domestic Heat-Pump System, *Applied Energy*, **80(3)**: 307-326 (2005).

[16] Dikici A., Akbulut A., An Exergetic Performance Evaluation of Multiple Source Heat Pump Systems, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **33(12)**: 1117-1138 (2011).

[17] Nuñez M.P., Exergy Analysis and Optimization of a Solar-Assisted Heat Pump, *Energy*, **23(4)**: 337-344 (1998).

[18] Badescu V., First and Second Law Analysis of a Solar Assisted Heat Pump Based Heating System, *Energy Conversion and Management*, **43(18)**: 2539-2552 (2002).

[19] Hepbasli A., Akdemir O., Energy and Exergy Analysis of a Ground Source (Geothermal) Heat Pump System, *Energy conversion and management*, **45(5)**: 737-753 (2004).

[20] Li Y., Wang R., Wu J., Xu Y., Experimental Performance Analysis on a Direct-Expansion Solar-Assisted Heat Pump Water Heater, *Applied Thermal Engineering*, **27(17-18)**: 2858-2868 (2007).

[21] Kuang Y., Sumathy K., Wang R., Study on a Direct-Expansion Solar-Assisted Heat Pump Water Heating System, *International Journal of Energy Research*, **27(5)**: 531-548 (2003).

[22] Hepbasli A., Exergetic Modeling and Assessment of Solar Assisted Domestic Hot Water Tank Integrated Ground-Source Heat Pump Systems for Residences, *Energy and Buildings*, **39(12)**: 1211-1217 (2007).

[23] Li Y., Wang R., Wu J., Xu Y., Experimental Performance Analysis and Optimization of a Direct Expansion Solar-Assisted Heat Pump Water Heater, *Energy*, **32(8)**: 1361-1374 (2007).

[24] Ahmadi M.H., *Ghazvini M., Sadeghzadeh M., Alhuyi Nazari M., Kumar R.r, Naeimi A., Ming T.*, Solar Power Technology for Electricity Generation: A Critical Review, *Energy Science & Engineering*, **6(5)**: 340-361 (2018).

[25] Ahmadi M.H., Baghban A., Sadeghzadeh M., Zamen M., Mosavi A., Shamshirband Sh., Kumar R., Mohammadi-Khanaposhtani M., Evaluation of Electrical Efficiency of Photovoltaic Thermal Solar Collector, *Engineering Applications of Computational Fluid Mechanics*, **14(1)**: 545-565 (2020).

[26] Chaturvedi S., Chiang Y., Roberts Jr A., "Analysis of Two-Phase Flow Solar Collectors with Application to Heat Pumps," (1982).

[27] Cengel Y.A., Boles M.A., Kanoğlu M., "Thermodynamics: an Engineering Approach". McGraw-hill New York, (2011).

[28] Treichel C., Cruickshank C.A., Energy Analysis of Heat Pump Water Heaters Coupled with Air-Based Solar Thermal Collectors in Canada and the United States, *Energy*, **221**: 119801 (2021).

[29] Fani M., Norouzi N., Ramezani M., Energy, Exergy, and Exergoeconomic Analysis of Solar Thermal Power Plant Hybrid with Designed PCM Storage, *International Journal of Air-Conditioning and Refrigeration*, **28(04)**: 2050030 (2020).

[30] Chua K.J., Chou S.K., Yang W., Advances in Heat Pump Systems: A Review, *Applied Energy*, **87(12)**: 3611-3624 (2010).

[31] Kariman H., Hoseinzadeh S., Heyns P.S., Energetic and Exergetic Analysis of Evaporation Desalination System Integrated with Mechanical Vapor Recompression Circulation, *Case Studies in Thermal Engineering*, **16**: 100548 (2019).

[32] Norouzi N., Jafarabadi Z.B., Valizadeh G., Hemmati M.H., Khajehpour H., Energy, Exergy, and Exergoeconomic (3E) Analysis of Gas Liquefaction and Gas Associated Liquids Recovery Co-Process Based on the Mixed Fluid Cascade Refrigeration Systems, *Iran. J. Chem. Chem. Eng. (IJCCE)*, **41(3)**: 1391-1410 (2022).

[33] Hoseinzadeh S., Garcia D.A., Numerical Analysis of Thermal, Fluid, and Electrical Performance of a Photovoltaic Thermal Collector at New Micro-Channels Geometry, *Journal of Energy Resources Technology*, **144(6)**: (2022).

[34] Ji J., Pei G., Chow T., Liu K., He H., Lu J., Han C., Experimental Study of Photovoltaic Solar Assisted Heat Pump System, *Solar Energy*, **82(1)**: 43-52 (2008).

[35] Omer A.M., Energy, Environment and Sustainable Development, *Renewable and Sustainable Energy Reviews*, **12(9)**: 2265-2300 (2008).

[36] Dincer I., Rosen M.A., "Exergy: Energy, Environment and Sustainable Development". Newnes, (2012).

[37] Hoseinzadeh S., Yargholi R., Kariman H., Heyns P.S., Exergoeconomic Analysis and Optimization of Reverse Osmosis Desalination Integrated with Geothermal Energy, *Environmental Progress & Sustainable Energy*, **39(5)**: e13405 (2020).

[38] Norouzi N., Talebi S., Exergy, Economical and Environmental Analysis of a Natural Gas Direct Chemical Looping Carbon Capture and Formic Acid-Based Hydrogen Storage System, *Iran. J. Chem. Chem. Eng. (IJCCE)*, **41(4):** 1436-1457(2022).

[39] Bejan A., "Convection Heat Transfer", John Wiley & Sons, Inc. (2013).

[40] Dincer I., Rosen M.A., "Thermal Energy Storage Systems and Applications", John Wiley & Sons, (2021).

[41] Yargholi R., Kariman H., Hoseinzadeh S., Bidi M., Naseri A., Modeling and Advanced Exergy Analysis of Integrated Reverse Osmosis Desalination with Geothermal Energy, *Water Supply*, **20(3)**: 984-996 (2020).

[42] Gilani, H. A., Hoseinzadeh, S., Techno-Economic Study of Compound Parabolic Collector in Solar Water Heating System in the Northern Hemisphere, *Applied Thermal Engineering*,**190**: 116756 (2021).

[43] Khoshgoftar Manesh M., Amidpour M., Hamedi M., Optimization of the Coupling of Pressurized Water Nuclear Reactors And Multistage Flash Desalination Plant by Evolutionary Algorithms and Thermoeconomic Method, *International Journal of Energy Research*, **33(1)**: 77-99 (2009).

[44] Kariman, H., Hoseinzadeh, S., Heyns, P. S., Sohani, A., Modeling and Exergy Analysis of Domestic MED Desalination with Brine Tank, *Desalination and Water Treatment* **197:** 1-13 (2020).

[45] Norouzi N., Hydrogen Production in the Light of Sustainability: A Comparative Study on the Hydrogen Production Technologies Using the Sustainability Index Assessment Method, *Nuclear Engineering and Technology*, **54(4)**: 1288-1294 (2022).

[46] Norouzi N., Fani M., Talebi S., Exergetic Design And Analysis of a Nuclear SMR Reactor Tetrageneration (Combined Water, Heat, Power, and Chemicals) With Designed PCM Energy Storage and a CO_2 Gas Turbine Inner Cycle, *Nuclear Engineering and Technology*, **53(2)**: 677-687 (2021).

[47] Shakouri M., Ghadamian H., Hoseinzadeh S., Sohani A., Multi-Objective 4E Analysis for a Building Integrated Photovoltaic Thermal Double Skin Façade System, *Solar Energy*, **233**: 408-420 (2022).

[48] Jovijari F., Kosarineia A., Mehrpooya M., Nabhani N., Comprehensive Pinch-Exergy Analyzes of the NGL Recovery Process, *Gas Processing Journal*, (2021).

[49] Safarvand D., Aliazdeh M., Samipour Giri M., Jafarnejad M., Exergy Analysis of NGL Recovery Plant Using a Hybrid ACOR-BP Neural Network Modeling: A Case Study, *Asia-Pacific Journal of Chemical Engineering*, **10(1)**: 133-153 (2015).

[50] Farajollahi A., Hejazi A., Gazori H., Rostami M., Energy Analysis and Exergy of the System of Simultaneous Production of Power and Hydrogen with the Excitatory Gasification of Municipal Solid Waste, *Amirkabir Journal of Mechanical Engineering*, **53(11)**: 12-12 (2022).

[51] Ghorbani B., Hamedi M.-H., Amidpour M., Exergoeconomic Evaluation of an Integrated Nitrogen Rejection Unit with LNG and NGL Co-Production Processes Based on the MFC And Absorbtion Refrigeration Systems, *Gas Processing Journal*, **4(1)**: 1-28 (2016).

[52] Ansarinasab H., Mehrpooya M., Parivazh M.M., Evaluation of the Cryogenic Helium Recovery Process from Natural Gas Based on Flash Separation by Advanced Exergy Cost Method–Linde Modified Process, *Cryogenics*, **87**: 1-11 (2017).

[53] Ansarinasab H., Mehrpooya M., Mohammadi A., Advanced Exergy and Exergoeconomic Analyses of a Hydrogen Liquefaction Plant Equipped with Mixed Refrigerant System, *Journal of Cleaner Production*, **144**: 248-259 (2017).

[54] Norouzi N., Shiva N., Khajehpour H., Optimization of Energy Consumption in the Process of Dehumidification of Natural Gas, *Biointerface Research in Applied Chemistry*, **11**: 14634-14639 (2021).

[55] Hoseinzadeh S., Stephan Heyns P., Advanced Energy, Exergy, and Environmental (3E) Analyses and Optimizationof a Coal-Fired 400 MW Thermal Power Plant, *Journal of Energy Resources Technology*, **143(8)**: (2021).

[56] Esen H., Inalli M., Esen M., Pihtili K., Energy And Exergy Analysis of a Ground-Coupled Heat Pump System with Two Horizontal Ground Heat Exchangers, *Building and Environment*,**42(10)**: 3606-3615 (2007).

[57] Norouzi N., Hosseinpour M., Talebi S., Fani M., A 4E Analysis of Renewable Formic Acid Synthesis From the Electrochemical Reduction of Carbon Dioxide and Water: Studying Impacts of the Anolyte Material on the Performance of the Process, *Journal of Cleaner Production*, **293**: 126149 (2021).

[58] Hoseinzadeh S., Ghasemi M.H., Heyns S., Application of Hybrid Systems in Solution of Low Power Generation at Hot Seasons for Micro Hydro Systems, *Renewable Energy*, **160**:323-332 (2020).

[59] Anvari S., Saray R.K., Bahlouli K., Employing a New Optimization Strategy Based on Advanced Exergy Concept for Improvement of a Tri-Generation System, *Applied Thermal Engineering*, **113**: 1452-1463 (2017).

[60] Khajehpour H., Norouzi N., Shiva N., Folourdi R. M., Bahremani E.H., Exergy Analysis and Optimization of Natural Gas Liquids Recovery Unit, *International Journal of Air-Conditioning and Refrigeration*, **29(01)**: 2150005 (2021).

[61] Anvari S., Taghavifar H., Parvishi A., Thermo-Economical Consideration of Regenerative Organic Rankine Cycle Coupling with the Absorption Chiller Systems Incorporated in the Trigeneration System, *Energy Conversion and Management*, **148**: 317-329 (2017).

[62] Norouzi N., Talebi S., Najafi P., Thermal-Hydraulic Efficiency of a Modular Reactor Power Plant by Using the Second Law of Thermodynamic, *Annals of Nuclear Energy*, **151**: 107936 (2021).

[63] Nami H., Nemati A., Fard F.J., Conventional and Advanced Exergy Analyses of a Geothermal Driven Dual Fluid Organic Rankine Cycle (ORC), *Applied Thermal Engineering*, **122**: 59-70 (2017).

[64] Szargut J., Morris D.R., Steward F.R., Exergy Analysis of Thermal, *Chemical, and Metallurgical Processes*, 7-39 (1988).

[65] Kotas T., "The Exergy Method of Thermal Plant Analysis." Elsevier (2013).

[66] Dincer I., Cengel Y.A., Energy, Entropy and Exergy Concepts and their Roles in Thermal Engineering, *Entropy*, **3(3)**: 116-149 (2001).

[67] Heat C., "Power: Evaluating the Benefits of Greater Global Investment–IEA", Paris, (2008).