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Energetic and exergetic analysis of evaporation desalination system integrated with mechanical vapor recompression circulation

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ABSTRACT

Considering future crises on freshwater scarcity, a new type of industrial desalination equipment is investigated in this paper. This device is powered by electric energy to evaporate the wastewater and is environmentally friendly due to the recovery of rejected wastewater. In this paper, energy analysis is first carried out to identify the major energy-consuming equipment and the amount of electrical energy consumed in the system. The exergy analysis of the system showed that the most exergy destruction occurs in the boiler compartment and central heat exchanger. The system is designed for a tank capacity of approximately 11.3 m^3, so the freshwater output is 9.6 m^3, and we reported the freshwater production in every process. This process takes about 4.5 h. So the system's capacity is about 2200 lit/hour. Finally, using a two-objective genetic algorithm, the system was optimized to reduce energy consumption and increase freshwater production. Optimization results showed that 59.83 L of the freshwater per kWh generated.

1. Introduction

Water is abundant that covers three-quarters of the Earth's surface. But only 3% of these resources can be used. About 25% of the world's population does not have access to freshwater, and 80 countries face freshwater problems. Drought is expected to cause many issues around the globe [1]. The oceans and seas are vast water resources in the world, but a high percentage of impurities impact the direct use of these waters for various applications. Nowadays, with the help of different methods of freshwater supply, it is possible to produce freshwater in large volumes. Each of these methods requires energy that can be supplied by electrical, mechanical, or thermal energy. In general, existing methods can be divided into two groups of heat and membrane [2].

Choosing the best freshwater method depends on the location, geographic conditions of the area, the initial cost of the existing, and various other factors. The water produced by the thermal methods has a concentration of about 1 ppm, while the quality of the reverse osmosis process is about 10–500 ppm [3]. Shakouri et al. developed a model for a multi-effect desalination-thermal vapor compression (MED-TVC) dispenser to connect to the Lavan Island gas turbine unit, and then optimized the developed model by conducting a thermal electronic [4]. Laissaoui et al. performed the thermodynamic analysis of the combined, concentrated solar power (CSP) system. And the liquidation of the multi-effect desalination (MED), and tested the performance of both the water system and the solar

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Nomenclature

c_p	Specific heat capacity(kJ/kg.K)
D	Distillate water (m^3 or lit)
E_D	Exergy destruction(kJ)
E_{cv}	Energy of control volume(kJ)
$\dot{E}_i$	Input Exergy(kW)
$\dot{E}_e$	Output Exergy(kW)
Ex^{ph}	Physical Exergy (kJ)
GOR	Gain output ratio
h	Enthalpy (kJ/kg)
h_0	Enthalpy of ambient(kJ/kg)
$\dot{m}_i$	Mass flow (kg/s)
m_t	Total mass in the boiling chamber(kg)
M_B	Total Mass of brine water(kg)
M_D	Total Mass of distillate water(kg)
n	Number of circulation
P	Pressure(kpa)
Q	Heat transfer(kJ)
Qh	Power of heater(kW)
RPP	Power of roots pump(kW)
S_i	Entropy(kJ/kg.K)
s_0	Entropy of ambient(kJ/kg.K)
T	Temperature(K or C)
T_0	Ambient temperature(K or C)
t	Time(min or s)
Δt	Duration (s)
t_{cycle}	Time of central cycle
u	Internal energy(kJ/kg)
W	Work (kJ)
X_b	Salt concentration (ppm)
η	Efficiency of component
ρ	kg/m^3

system in northern Algeria. In the results of his research, 50 MW produced electrical energy and 22,568 m^3/day freshwaters [5]. Fathy et al. presented a thermodynamic model for the production of electrical energy and freshwater systems and introduced the optimal point for the production of power and freshwater. Their studies showed that the combined production system is about 20.6% more than the total cost per year compared to the individual mode. The power generation system included the heat recovery steam generator (HRSG) turbine, the steam turbine, as well as the multi-effect desalination-thermal vapor compression (MED-TVC) [6]. Almutari et al. presented a comprehensive model of power generation and water supply based on energy and exergy analysis with real data. The power generation system included the combined cycle and the freshwater production system of the multi-effect desalination-thermal vapor compression (MED-TVC) cycle. The results showed that the greatest source of irreversibility in multi-effect desalination (MED) systems occurs in the effects of thermo compressors [7]. Isfahani and colleagues proposed a systematic approach to the analysis and optimization of the multi-effect desalination-thermal vapor compression (MED-TVC) water system. In this research, the goal was to search for a minimum amount of total annual cost and maximum gain output ratio (GOR) value, using a genetic algorithm based on the neural network model. The optimized beam diagram showed that the multi-effect desalination-thermal vapor compression (MED-TVC) system has six effects compared to 3, 4, and 5 effects in a more optimal way [8].

Rezaei et al. evaluated the water production system of multi-effect desalination (MED) in Qeshm Island. They also evaluated other energy sources such as coal, oil, gas and nuclear cycles, achieved more optimal parameters [9], and evaluated a freshwater production system in Qeshm Island. The water desalination plant has a capacity of 18,000 cubic meters per day and a gas turbine of 250 MW. The total annual water cost and annual cost of the combined pipeline desalination system, the power water reactor (PWR) reactor and the pebble bed modular reactor (PBMR) are about 1.78, 1.49, 0.77 $/m3, and 94.74, 49.23 and 49.1 billion US dollars, respectively [10]. Hosseinzadeh et al. [11–13] investigated some systems optimization and exergy analysis. They studied thermal behavior of sub-systems, including collector temperature changes; heat exchanger and storage tank, and designed it to optimize the three-objective exergy efficiency, CO_2 distribution and production costs analyzed by using a 500 MW hybrid power generation system [14,15]. They also simulate a conventional cogeneration unit in Iran using a mathematical method to perform sensitivity analysis on environmental emissions and electricity prices [16–18].

Mokhtari et al. studied a hybrid system consisting of gas turbine, sweetener multi-effect desalination (MED) and reverse osmosis system for water and electricity production in Bashaghord. They found that using a gas turbine with a power greater than the demanded in a hybrid state, it could be lowered by 0.5 $/m^3 of produced water from $ 2.8 to $ 2.3 [19]. Adam et al. studied a thermodynamic and economic model for a combined system with energy sources. They have tried to design a Solar multi effect desalination-reverse osmosis (MED-RO) hybrid water desalination system for purifying water drainage in California. They found that the combined multi effect desalination-reverse osmosis (MED-RO) system works more efficiently than the independent multi effect desalination (MED) systems. Therefore, the use of a centralized solar energy concentrated solar power (CSP) source for generating electricity and heat without greenhouse gases is a significant principle [20].

As we discussed earlier, the problem of water scarcity has forced people to use less freshwater systems. Portable systems play an important role, and analyzing these systems in terms of energy and optimization can be very helpful in increasing freshwater production and reducing energy. In this study, we intend to introduce a new system of industrial desalination and examine the energy and exergy analysis and optimization of this system. The system that is currently similar to evaporative water desalination because it is evaporated akin to the osmotic system and the energy source is electrical. This type of desalination is called mechanical vapor recompression (MVR). The main advantage of this desalinization system is the return of energy in the system and the minimal use of thermal energy compared to other existing systems. It is also very suitable for preventing environmental pollution due to the full use of electrical energy. On the other hand, energy and exergy of this new system analyzed due to importance of the issue of energy and use of most of it and preventing its loss, the exergy analysis is done on this device, the most parts with exergy destruction is identified, which has not been done so far. and also the system optimized with a genetic algorithm [21–24].

2. System description

The schematic of a vacuum evaporator system of the type of forced circulation is shown in Fig. 1. The components of this system consist of two plate heat exchangers, a boiling brush boiler, a freshwater storage tank, an electric heater, a vacuum cleaner pump, a root pump, a centrifuge pump, a freshwater extraction pump, and water pipes.

This set has two cycles that flow in the first cycle of water and steam between a plate transducer and a boiling chamber so that evaporation takes place, and freshwater is produced and produced freshwater in another cycle. Which is stored in a freshwater tank and has exergy, extends from a heat exchanger to precipitate the saltwater entering the combustion chamber. This system is designed for different water production capacities. The area of the system is almost m^2 with an approximate capacity of 48 m^3, of freshwater per day. The inlet temperature of the salinewater is 298 K^0 and the fresh water temperature is about 308 K. From the main parts of the equipment, the pump system is a vacuum supplier, which should provide a compression equivalent to the saturation pressure of 333 K^0, 19.479 kPa, in its boiling chamber during the operation of the heater. In this system, a 115 kW electric heater is used and a 30 kW peak power pump is used. Cases like this one made by Condorchem Company can be good examples of this system [25].

The essential information is provided by the Condorchem Convergent Condenser Vacuum Convergent Evaporator System, which uses this information to validate the results [25].

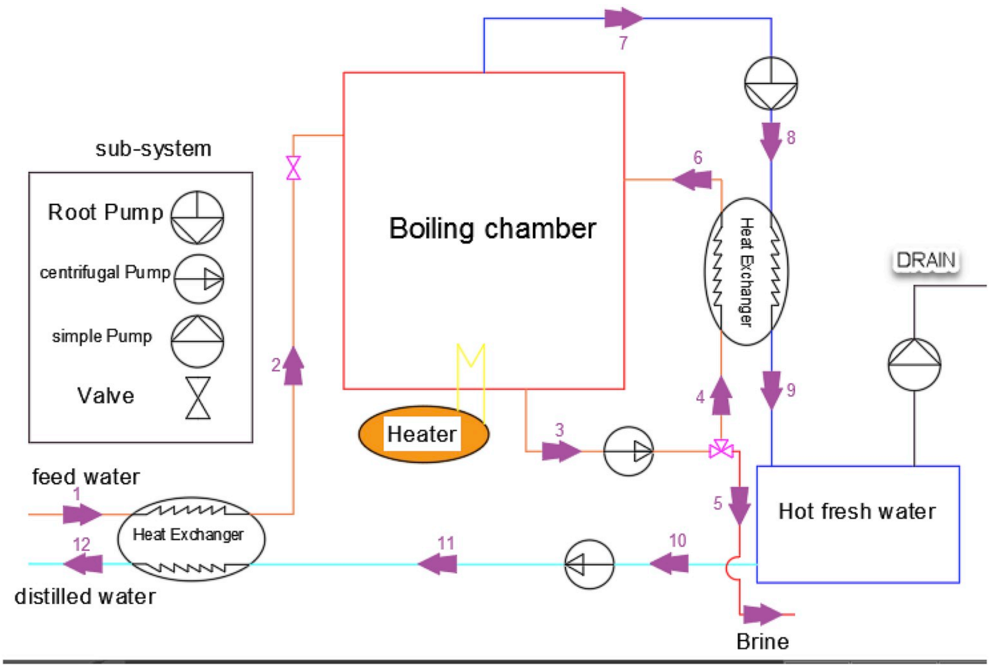


Fig. 1. Schematic of a vacuum evaporator system of the type of forced circulation.

3. Energy and exergy analysis and optimization

The most useful work that can be obtained from a certain amount of energy is called exergy. Generally, in the analysis of exergy, the main purpose is to determine the location and amount of production of Exergy destruction during the various processes of the thermodynamic cycle and the factors affecting their production. Hence, in addition to evaluating the performance of various components of the thermodynamic cycle, cyclic efficiency enhancement solutions are also identified. The exergy destruction of the system is obtained as follows [26]:

$$\dot{E}_D = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i e_i - \sum_e \dot{m}_e e_e \tag{1}$$

T^0 is the temperature of dead state, and T_j is the temperature of process state, and $Q^0{}_j$ is heat exchanged, and $W^0{}_{cv}$ is the work done on the system, and $e^0{}_j$ is the exergy output value and $e^0{}_e$ is the exergy input to the system and $E^0{}_D$ is the system exergy destruction value.

$$Ex^{ph} = m^0 \ * \ [(h - h_0) - T_0(s - s_0)] \tag{2}$$

In the physical exergy equation, m^0 is equal to the mass flow rate of the system, and h^0 is the enthalpy of the dead, and s^0 is the value of the entropy of the dead.

Exergy destruction in pumps.

The indexes refer to each moment of the cycle and the conditions governing that moment, which are equal to the numbers in Fig. 1.

$$E_{D-pumps} = \sum_i E_i^0 - \sum_e E_e^0 + \sum W_{pump}^0 \tag{3}$$

$$E_{D-pump}^0 = E_3^0 + E_7^0 + E_{10}^0 - E_4^0 - E_8^0 - E_{11}^0 + W_{rootpump}^0 + W_{circpump}^0 + W_{pump}^0 \tag{4}$$

The amount of produced water is obtained from the following equation;

$$M_d^0 = \frac{\left(Q^0 - \left(M_{0f} \times C_{pf} \times \left(T_b - T_f\right)\right)\right.}{H_{fg}} \tag{5}$$

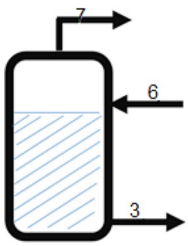
That C_{pf} is equal to the thermal capacity of feed water, and T_f is inlet temperature of the feed water and the H_{fg} is equal to the heat of evaporation of the water under evaporation conditions. At the end, M_{0f} is equal to the amount of feed water.

$$GOR = \frac{Water\_production}{Power\_consumption} \tag{6}$$

The efficiency value in desalination systems is defined as the GOR value. GOR is equal to the amount of freshwater produced and the amount of energy used to produce freshwater. It is a unit without a unit.

3.1. Mathematical modeling

Boiling chamber



$$m_3^0 = m_6^0 \tag{7}$$

$$m_t(n) = m_t(n+1) + m_7^0(n)^* t_{cycle} \tag{8}$$

M_t is the flow rate at any moment of the system and the t_{cycle} of the system rotation

$$\Delta En)_{cycle} = M_t(n+1) * u(n+1) - M_t(n) * u(n) \tag{9}$$

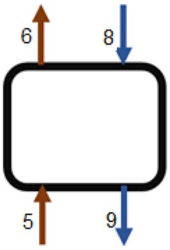
U is equal to the amount of internal energy in any part of the system.

$$Q^0 = \frac{M_t * c_p * \Delta t}{t} \tag{10}$$

C_p is equal to the heat transfer coefficient.
And if the heater is clear, because the energy is converted into thermal energy, the total energy is exergy destruction.

$$E_D^0 = \sum_i E_i^0 - \sum_e E_e^0 + Q_{heater}^0 \tag{11}$$

Central heat exchanger.



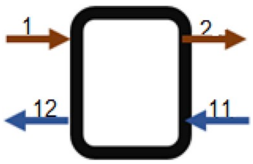
$$m_8^0 = m_9^0 \tag{12}$$

$$m_4^0 = m_6^0 \tag{13}$$

$$H_6 - H_4 = H_8 - H_9 \tag{14}$$

$$E_D^0 = \left(E_8^0 - E_9^0\right) - \left(E_6^0 - E_4^0\right) \tag{15}$$

heat exchanger2.



$$m_1^0 = 0.85 * m_{11}^0 \tag{16}$$

$$H_2 - H_1 = H_{11} - H_{12} \tag{17}$$

$$m_1^0 * (h_2 - h_1) = m_{11}^0 * (h_{11} - h_{12}) \tag{18}$$

$$0.85 * (h_2 - h_1) = (h_{11} - h_{12}) \tag{19}$$

$$E_D^0 = \left(E_{11}^0 - E_{12}^0\right) - \left(E_2^0 - E_1^0\right) \tag{20}$$

$$m_7^0 = m_8^0 \tag{21}$$

$$m_7^0 * (h_8 - h_7) = \frac{W_{rootPump}}{\eta_{rootPump}} \tag{22}$$

$\eta_{rootPump}$ is equal to efficiency and is equal to 0.9.
Circulation pump.

$$m_3^0 * (h_4 - h_3) = \frac{W_{circPump}}{\eta_{circPump}} \tag{23}$$

General pump.

$$m_{11}^0 = m_{12}^0 \tag{24}$$

$$m_{10}^0 * (h_{11} - h_{10}) = \frac{W_{Pump}}{\eta_{Pump}} \tag{25}$$

$$power - consumption = \mathrm{Q}^0 + W_{rootpump}^0 + W_{circpump}^0 + W_{generalpump}^0 \tag{26}$$

The circulation pump and general pump efficiency are equal to 0.8.

3.2. Optimization and objective

The main objectives of this study are to achieve the maximum amount of freshwater produced in the system, while the amount of energy consumed will reach its minimum. The maximum amount of freshwater per unit liters per hour is raised. The main electrical energy of this system is consumed in the electric heater and the root pump, and very little in the other pumps are used to provide the required pressure.

Objective functions:

$$\phi = \frac{M_d^0}{power - consumption} = \mathrm{GOR} \tag{27}$$

$$MAX \ \ \mathrm{OF} = \phi$$

The thermodynamic analysis of this system includes many parameters and variables, each of which can be considered as a decision variable. However, since running this cycle at each repeat frequency of several thousand replicates is spent a long time. The variables are given in the following Table (1).

To optimize a cycle, we need to apply the upper and lower constraints on the decision variables to get the right answer. These variables are presented in a separate Table (2).

3.3. Description of the optimization algorithm

The genetic algorithm was first introduced by John Holand and was later developed by his students [27]. This algorithm is a method by which a population with a natural selection and coupling operators, and mutations and inversions inspired by biological genetics, are transmitted to a new population. This evolutionary algorithm is generated randomly from the population of individuals. In each generation, a population is proportional to the objective function. Number of the population are selected from the current population and the rest are eliminated or modified to be used in the new population. This new population is used to repeat the algorithm.

This algorithm ends when the algorithm is terminated in such a way as to be satisfied. For example, these conditions can be tangible in answer to the case [28]. In Table (3), the value of the parameters set for the genetic algorithm is also shown.

As mentioned, the optimization algorithm selected for the optimization process of this system is the genetic algorithm. This algorithm has its characteristic series. To use this algorithm in MATLAB software [29,30] the population characteristics and the

Table 1
Decision variables of optimization.

Temperature of boiling chamber	T
Power of electrical heater	Q_h
Power of root pump	RP_P
Mass flow of the circulation	$\dot{m}$
Salt concentration	X_b

Table 2
Physical constraints (feasibility conditions).

T (K^0)	$50 \le T \le 70$
Q_h (kW)	$100 \le Qh \le 120$
RP_P (kW)	$10 \le RPP \le 30$
$\dot{m}$(kg/s)	$10 \le \dot{m} \le 20$
X_b (ppm)	$X_b \le 70000$

Table 3
The value of the parameters set for the genetic algorithm.

Tuning parameters	value
Population size	50
Maximum no. of generation	30
P_c (Probability of crossover)	70%
P_m (Probability of mutation)	1%
No. of crossover point	2
Selection process	Tournament
Tournament size	2

maximum number of mutations and other items are defined in this Table (3).

4. Results

The results of the exergy analysis of this system indicate that most exergy destruction occurs in its boiling chamber. Diagram (Fig. 2) shows the magnitude of exergy destruction in each of the cycles. The central heat exchanger of this cycle also has extreme exergy destruction due to working in higher temperatures.

In Fig. 3, the graph shows the variations in the concentration of the solution in the boiling chamber in terms of temperature in the case where the other variables are constant, and only the vacuum system is affected. This diagram shows that the higher the temperature, the number of stages of evaporation decreases, and the capacity of the cycle increases, But higher temperatures reduce vacuum pressure, which does not increase the ability to reduce vacuum pressure. Therefore, the lower temperatures that have higher vacuum pressure are more cost-effective.

In Fig. 4, the evaporation duration of the water is shown regardless of the operating time of the electric heater and the time of discharge of salt sediment. In this diagram, it is also known that by reducing the vacuum temperature of 3 K, less than 1% of the time of

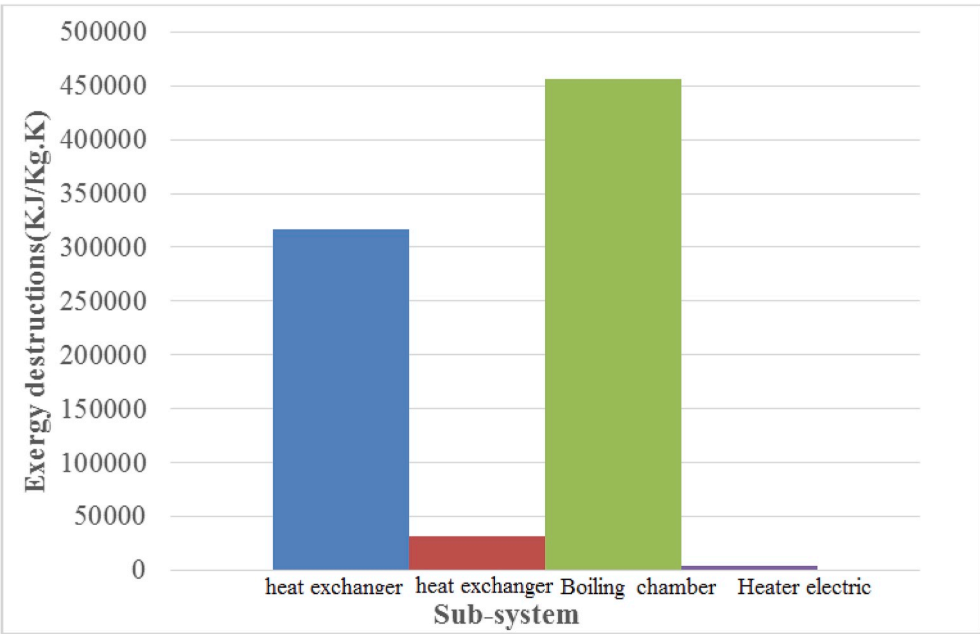


Fig. 2. Exergy destruction in sub-system.

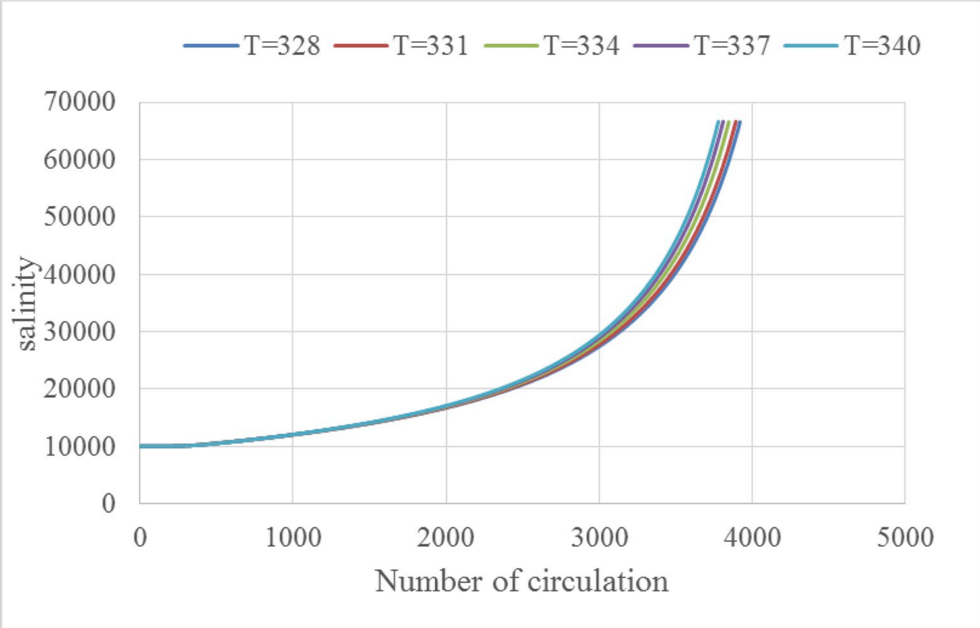


Fig. 3. Concentration changes with temperature changes.

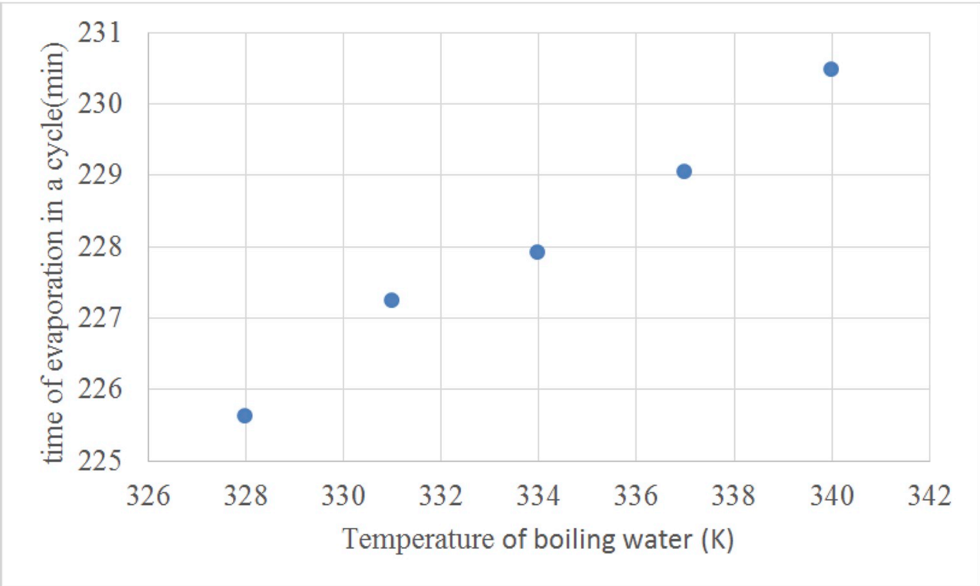


Fig. 4. Time of evaporation in a cycle(min).

evaporation of the cycle is reduced, and it is more economical than the operating conditions of the system are at lower temperatures and higher vacuum pressure.

In Fig. 5, this time, electric power consumption is shown at different temperatures. The higher the boiling temperature of the boiler, in addition to the vacuum pressure, the less the electric heater consumes more, and the maximum electrical energy consumption occurs at maximum temperature.

Finally, a two-objective analysis of the genetic algorithm was performed on the device as mentioned earlier to minimize electrical energy consumption and the maximum amount of freshwater production. This analysis showed that, as expected, increasing the amount of energy can increase the amount of freshwater produced. This increase is so valuable that freshwater is produced to the amount of electricity consumed. Therefore, by defining the GOR parameter in the previous section, the optimal value of the GOR parameter is represented by the graph (Fig. 6).

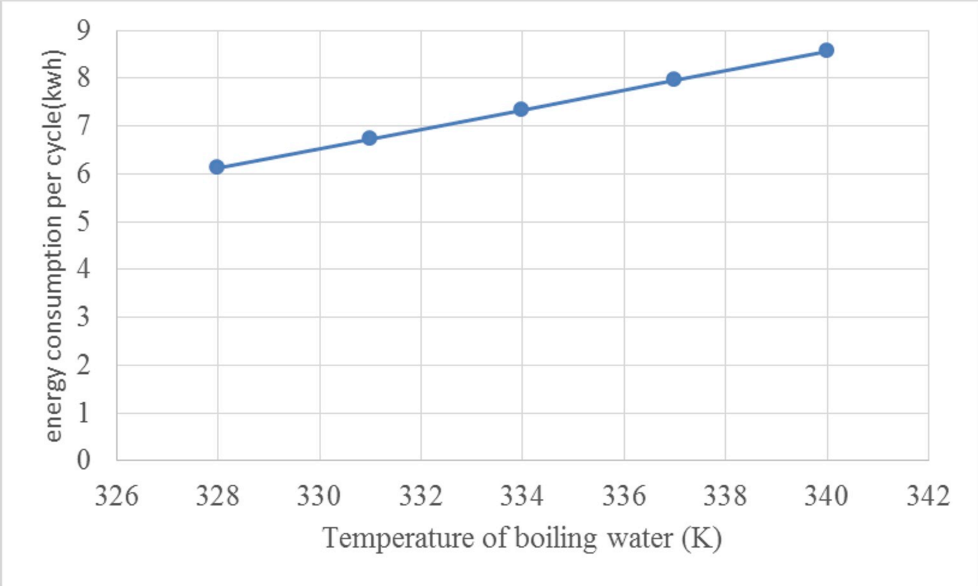


Fig. 5. energy consumption per cycle(kwh).

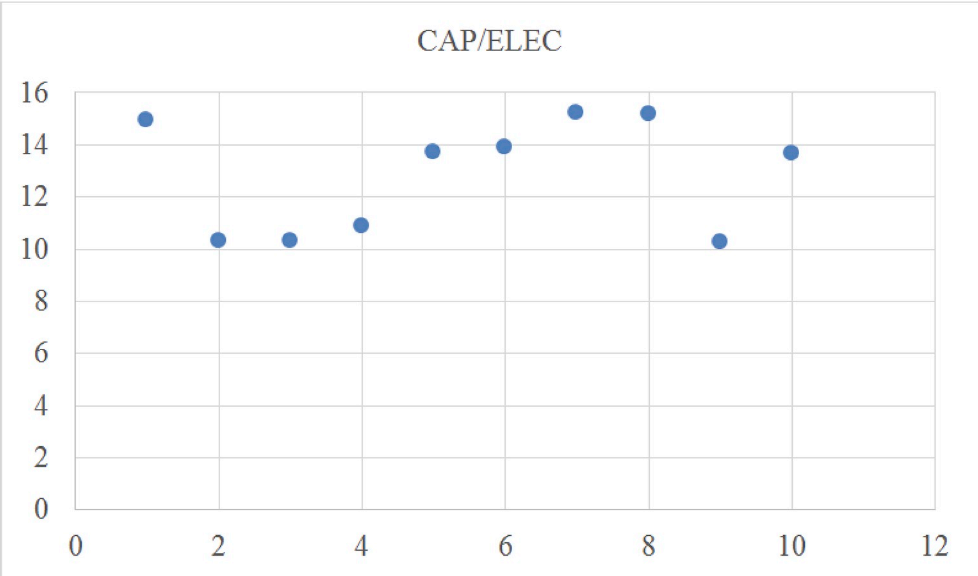


Fig. 6. Capacity per energy consumption in any point of PARETO.

Each of the points in (Fig. 7) represents a combination of decision variables in the optimization process, each of which can be an optimal point for the desalination system. But at one point, the highest GOR value is obtained, and this value is 59.83. In other words, under certain conditions, the amount of freshwater output per kilowatt-hour is equal to 59.83 units of freshwater. The number of PARETO points showed in Table 4.

Using the PARETO function points, we can obtain the optimum temperature that produces the lowest power consumption and the best freshwater capacity and production, all of which are presented in Table 4.

As can be seen in Table (4), the amount of water produced at each temperature increases with increasing energy consumption. After examining the number of points in the PARETO diagram, it is concluded that the optimum value at 328.69 K and 160.437 kWh is 59.83, which can be approximately 60 L of freshwater produced per electricity consumption (kWh) is considered.

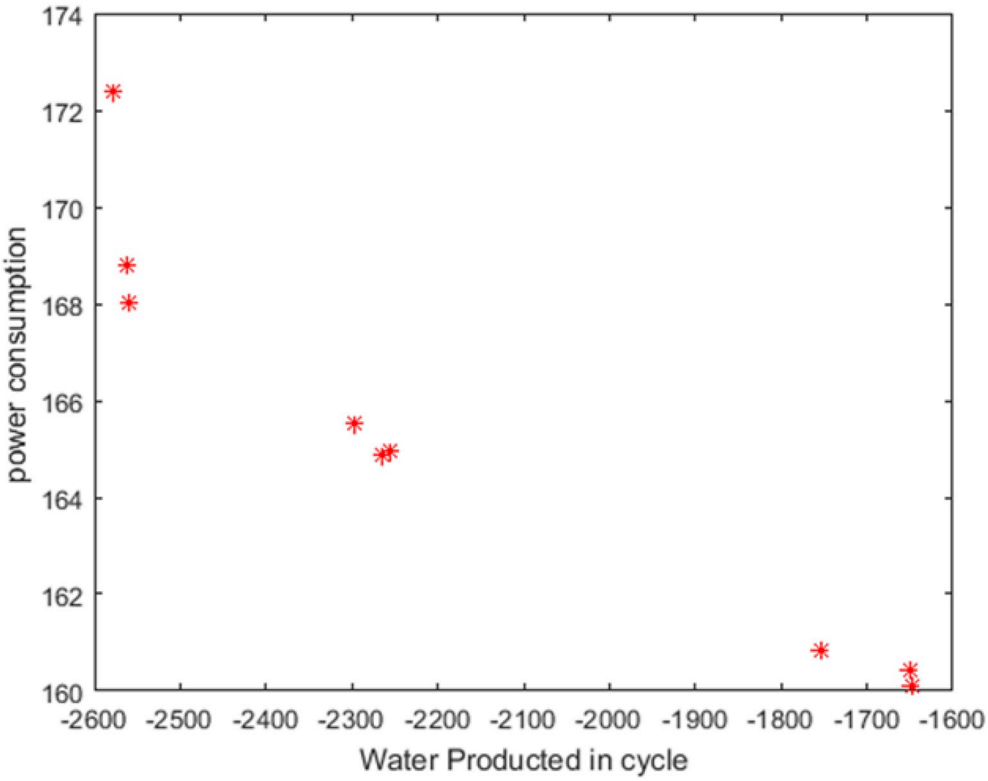


Fig. 7. PARETO diagram of this optimization.

Table 4
Number of PARETO points.

	Temperature (K^0)	power of root(Kw)	mass of circulation (kg/s)	power of heater(Kw)	Capacity (lit/day)	Electricity consumption (KWh)	Water production PER Electricity consumption
1	333.32	39.095	16.138	119.391	2579.150	172.378	55.69,152
2	328.44	20.923	10.971	116.750	1648.170	160.102	59.96,147
3	328.44	20.923	10.971	116.750	1648.170	160.102	59.96,147
4	328.44	22.721	10.971	116.750	1753.628	160.821	59.6935
5	329.23	32.228	11.222	118.870	2265.437	164.894	58.2189
6	329.23	33.043	11.222	118.870	2298.065	165.516	58.00013
7	330.92	38.314	18.118	118.097	2559.234	168.019	57.13,625
8	331.44	38.314	17.922	119.189	2561.159	168.781	56.87,813
9	328.69	20.923	10.942	116.590	1648.673	160.437	59.83,624
10	329.23	32.047	11.222	118.98	2254.721	164.950	58.19,929

5. Conclusion

In this paper, energy and exergy analysis was carried out on a new type of water desalination based on the evaporation of water. This technology of desalination uses a forced rotation of the energy of distilled water into saline water to maximize the use of available energy. Finally, the genetic algorithm was thermodynamically optimized. Exergy analysis of the process showed that most of the irreversibility occurred inside its boiling chamber. Therefore, with more focus on the boiling chamber, it can achieve higher exergy efficiency. Also, the highest consumption of exergy occurs in the form of electrical energy in the root pump. In this research, a new definition of the gain output ratio of desalination of water is made. And it was shown that this type of desalination could best produce about 60 L of freshwater per kilowatt-hour. Of course, this amount is small on the tested scale, but it can be much more economical on an industrial scale.

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