A comprehensive exergoeconomic analysis of absorption power and cooling cogeneration cycles based on Kalina, Part 2: Parametric study and optimization

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A comprehensive exergoeconomic comparison of the absorption power and cooling cogeneration cycles based on Kalina is investigated in this study. After thermodynamic and exergoeconomic simulation of the double effect absorption refrigeration/Kalina as well as the first and second configurations of simple absorption refrigeration/Kalina cogeneration cycles, in this part, a widespread parametric study is done and the effects of the simultaneous variations of all studied cogeneration cycles operating parameters are examined on the thermodynamic and exergoeconomic performance of the cogeneration cycles. Also, for a better comparison of the considered cycles, the optimization is done and the considered cogeneration cycles are comprised regarding to five objective functions including the minimum unit cost of products, maximum energy and exergy efficiencies, minimum unit cost of produced exergy and minimum the sum of exergy destruction and capital investment cost rates. Finally, the payback period of the studied cogeneration cycles is calculated in all optimum states. The results show that the minimum unit cost of products for the first configuration of SAR/Kalina cycle is 16.46\% and 9.27\% less than the corresponding values for the DEAR/Kalina cycle and the second configuration of SAR/Kalina cycle, respectively. Also, the value of $C_0 + Z$ parameter for the first configuration of SAR/Kalina cogeneration cycle is 28.32\% and 33.12\% less than the corresponding values for the second configuration of SAR/Kalina cycle and DEAR/Kalina cycle, respectively. Also, in all optimum states except for the minimum unit cost of produced exergy, the first configuration of SAR/Kalina cycle has the lowest amount of payback period.

1. Introduction

Today, regarding the deficiency of fossil fuel resources and because of the environmental impacts of burning fossil fuels, the use of cogeneration systems and heat recovery from medium and high temperature heat sources have become inevitable. Using cogeneration systems will increase the efficiency of energy conversion systems and reduces NOx emissions of exhaust gases from industrial units, diesel engines, gas turbines, etc., by reducing the temperature of these exhaust gases. The absorption power and cooling cogeneration systems that have been provided in recent years are fully compatible with long-term purposes. Because, on one hand, the efficiency of these types of cogeneration systems is more than conventional energy conversion systems, and on the other hand, with respect to the existence of steam generator in these cogeneration cycles, the use of exhaust gases as the heat source of these cycles is feasible. So, heat recovery of exhaust gases from industrial units can be possible by using this type of cogeneration cycles. In recent years, the more attention has been paid to absorption power and cooling cogeneration systems. In part 1 of this paper, it was pointed out some important studies have been conducted on these types of cogeneration cycles [1-13]. In the following, some other researches that have been done in recent years will be mentioned. Hasan et al. [14] studied the proposed cycle by Goswami in terms of the first and second law of thermodynamics. In this study, they used a solar heat source with temperatures between 57°C and 197°C. In this cycle the produced power and cooling were 16.9% and 1.26% of the energy supplied to the cycle, respectively. This cycle was also optimized for the maximum second law efficiency, which was obtained 65.8% at the heat source temperature of 147°C. Also, the results of the exergy analysis showed that the absorber exergy destruction rate is 44\% of overall exergy destruction rate of the cycle. This value was 16\% and 24\% for the rectifier and heat exchanger, respectively. Vidal et al. [15] analyzed the proposed power and cooling cogeneration cycle by Goswami from the exergy viewpoint. They used the Redich-Kwong-Soave equation to...
obtain the thermophysical properties of ammonia-water solution. Also, this cycle is analyzed from both reversible and irreversible viewpoints and the value of exergy destruction rate for all components is obtained. In a reversible state for the cycle, when the temperature of the heat source was 125 °C and 150 °C, the exergy efficiency for the cycle reaches 53% and 51%, respectively. Also, although the amount of produced cooling is less than generated electricity in this cycle, when the low temperature heat source is used, both electricity and cooling can be produced simultaneously. Zhang and Lior [16] analyzed the cycle with the internal cooling source for the rectification process. They showed that for a low temperature heat source, the first scheme has the higher RUE value than the second one. Also, in the optimal value of RUE, the first law efficiency in the first scheme is greater than the corresponding value for the second one. A parametric study was also performed on these cycles and GRG (Generalized Reduced Gradient) algorithm was used for optimization. Fontalvo et al. [19] examined two configurations of the Goswami cycle. In the first configuration, the cooling source for the rectifier is internally and in the second one, the source is considered externally. Exergy analysis of the cycles showed that the absorber, boiler and turbine have the highest amount of exergy destruction rate among the components of the cycles. The results obtained from the comparison of the cycles indicate that the cycle with the internal cooling source for the rectifier has the lower amount of exergy destruction rate than the cycle with the external cooling source for the rectifier. As a result, the exergy performance of the cycle with the internal cooling source is better. It is also observed that the existence of superheater after the rectifier will reduce the exergy destruction rate of the cycles. Demirkaya et al. [20] implemented a multi-objective optimization on Goswami cycle using a genetic algorithm. The generated electricity, produced heat and first and second law efficiencies are selected as the objective functions. They considered two designs in their research. In the first design, the Goswami cycle was selected as the downstream cycle, and in the second design, the Goswami cycle was considered as the main cycle and geothermal fluid was used as the heat source of these cycles. The temperature of outlet mixture from the boiler was between 70 °C and 150 °C for the first design, between 150 °C and 250 °C for the second design and the ammonia-water solution concentration was considered between 0.2 and 0.65 for the optimization. In the first design, the maximum values of produced power and exergy efficiency were obtained at the maximum of the boiler outlet temperature (150 °C). In the second design, the maximum value of exergy efficiency was obtained in the maximum
value of the boiler outlet temperature and the minimum value of the ammonia-water concentration. Wang et al. [21] presented a power and cooling cogeneration cycle by modifying the Kalina cycle and analyzed the cycle from the energy and exergy viewpoints. Also, the exergy destruction rate of the cycle is calculated and a parametric analysis is performed to determine the effects of the operating parameters on the thermodynamic performance of the cycle. The results show that after the evaporator, the highest amounts of exergy destruction rate occur in the condensers, and therefore, these components are critical from the exergy viewpoint. It was also shown that with the increase of the first separator temperature, the values of the first and second law efficiencies are increased. Yang et al. [22] proposed a novel power and ejector-refrigeration combined cycle in which the zeotropic mixture (isobutane/pentane) is selected as the working fluid. The thermodynamic performance of the combined cycle with different fluid composition is investigated and compared with a conventional power and refrigeration combined cycle. The results show that the maximum exergy efficiency of the novel combined cycle is obtained 10.29% with the isobutane/pentane (40%/60%) mixture. Also, the maximum value of thermal efficiency is calculated 10.77% with the isobutane/pentane (70%/30%) mixture. Also, the parametric study indicates that the thermodynamic performance of the combined cycle is increased with decreasing the condenser temperature. The experimental study on a novel resorption system for simultaneous production of electricity and cooling is done by Jing et al. [23]. Because of there is no ammonia liquid in the system, resorption refrigeration systems are safety and have the simple structure. The proposed cogeneration cycle consists of three high temperature salt unit beds, three low temperature salt unit beds, one expander, two oil valves, three ammonia valves, four water valves and connection pipes. Chemical working pair of MnCl2-CaCl2-NH3 is selected in this system. The experimental results indicate that the maximum amounts of cooling rate and electricity of 2.98 kW and 253 W are obtained, respectively. Also it is shown that the thermal efficiency of the system is increased from 29.3% to 41.7% and then is decreased to 40.7%. Rashidi et al. [24] analyzed a power and cooling combined cycle from the energy and economic viewpoints. In this part, a comprehensive parametric study is performed and the effects of simultaneous variations of different operating parameters are examined on the thermodynamic and exergoeconomic parameters in all studied cogeneration cycles. Then, the optimization of the cycles is done and these considered cogeneration cycles are compared regarding five objective functions. Finally, the payback period for all studied cogeneration cycles in different optimum states is calculated.

2. Considered cogeneration cycles

Ammonia-water double effect absorption refrigeration/Kalina cogeneration cycle and two configurations of the simple ammonia-water absorption refrigeration/Kalina) are studied for heat recovery from a high temperature heat source such as exhaust gasses from diesel engine. In part 1 of this paper [28], the thermodynamic and exergoeconomic analysis methods as well as the properties of each point in all studied cogeneration cycles are presented and discussed. The contributions of various components of these cogeneration cycles in the overall amount of $C_{0} + Z$ parameter and overall exergy destruction rate are provided and compared. In this part, the comprehensive parametric study is performed and the effects of simultaneous variations of different operating parameters are examined on the thermodynamic and exergoeconomic parameters in all studied cogeneration cycles. Then, the optimization of the cycles is done and these considered cogeneration cycles are compared regarding five objective functions. Finally, the payback period for all studied cogeneration cycles in different optimum states is calculated.
generator and the other part enters the second absorber after passing through the third throttle valve. The outlet saturated liquid from the second absorber reaches the highest pressure level of the cogeneration cycle using the third pump. The pump outlet fluid is superheated by the heat of diesel engine exhaust gasses. With expanding the superheated mixture through the steam turbine, the power is generated. The outlet stream from the turbine is mixed with the saturated liquid exited from the high temperature steam generator and the mixture enters the first absorber.

Also, Figs. 2 and 3 show two configurations of the combination of the Kalina cycle and the water-ammonia absorption refrigeration cycle. The components of the first configuration which is shown in Fig. 2 include absorber 1 at the lowest pressure level, absorber 2 and evaporator at the second pressure level, steam generator, rectifier and condenser at the third pressure level and boiler at the highest pressure level of the cogeneration cycle. The saturated liquid from the lowest pressure absorber after passing through the first pump is divided into two parts. One part moves to the second absorber. The outlet saturated...
Fig. 4. The temperature variations of the low temperature steam generator on the performance of DEAR/Kalina cogeneration cycle.

Fig. 5. The highest pressure level variations on the performance of DEAR/Kalina cogeneration cycle.
liquid from the second absorber enters the boiler after passing through the second pump. The boiler outlet superheated mixture expands to the lowest pressure level of the cogeneration cycle in the turbine and then enters the first absorber after heating the second portion of the outlet fluid from the first pump. Therefore, the second part of the outlet fluid from the first pump enters the rectifier after taking the heat in the first and second heat exchangers. The outlet saturated liquid from the rectifier enters the steam generator. The saturated vapor from the steam generator (at the generator temperature) returns to the rectifier, and the saturated liquid portion moves to the lowest pressure absorber after passing through the third heat exchanger, first heat exchanger and first throttle valve, respectively. Also, the saturated vapor rejected from the rectifier enters the condenser and at the condenser temperature, the percentage of this mixture returns to the rectifier. The rest of this mixture enters the evaporator through passing the second throttle valve and the cooling is produced.

The components of the second configuration which is shown in Fig. 3 include absorber 2 at the lowest pressure level, evaporator and absorber 1 at the second pressure level, steam generator, rectifier and condenser at the third pressure level and boiler at the highest pressure level of the cogeneration cycle. The outlet saturated liquid from the second absorber is divided into two parts. The pressure of the first part is reached the third pressure level of the cogeneration cycle using the first pump and enters the rectifier after passing through the first and second heat exchangers, respectively. The outlet saturated liquid from the rectifier enters the steam generator. The saturated vapor from the steam generator (at the generator temperature) returns to the rectifier, and the saturated liquid portion moves to the lowest pressure absorber after passing through the third heat exchanger, first heat exchanger and the second throttle valve, respectively. Also, the saturated vapor rejected from the rectifier enters the condenser and at the condenser temperature, the percentage of this mixture returns to the rectifier. The rest of this mixture enters the evaporator after passing through the fifth heat exchanger and first throttle valve. The evaporator outlet mixture also enters the first absorber through the fifth heat exchanger. The pressure of the second part of the saturated liquid from the first absorber is reached the highest pressure level of the cogeneration cycle using the second pump. This mixture enters the boiler after taking the heat in the third and fourth heat exchangers, respectively. The superheated mixture from the boiler expands in the turbine and generates power. The outlet stream from the turbine returns the lowest pressure absorber after heating the outlet fluid from the second pump. The

Fig. 6. The effect of simultaneous variations of the temperature of the low temperature steam generator and the high pressure level of the cycle on the performance of DEAR/Kalina cogeneration cycle.
saturated fluid exited from the lowest pressure absorber is also reached the second pressure level of the cogeneration cycle using the third pump.

Also, in part 1 of this study, the exergoeconomic analysis method as well as thermodynamic and exergoeconomic simulation of the considered cycles are presented and described. But for understanding the parameters used in the parametric study and optimization of the cogeneration cycles, a summary of the exergoeconomic analysis of the cycles is presented in the following.

The cost flow rate balance equation for each component of the cogeneration cycles is written as following:

$$\sum_{i} C_{c,i} + C_{w,i} = C_{q,i} + \sum_{i} C_{l,i} + Z_k$$

(1)

where \(i\) and \(e\) indices denote the input and output stream of the component \(k\), \(Z_k\) is the capital investment cost rate of the component \(k\) and \(C_c\) and \(C_w\) represent the cost rate associated with work and heat transfer, respectively. \(C_l\) and \(C_q\) are calculated as follows:

$$\dot{C}_l = c_l \dot{W}$$

(2)

$$\dot{C}_q = c_q \left( \frac{1}{T_i} - \frac{1}{T} \right)$$

(3)

So, Eq. (1) can be expressed as following:

$$\sum (c_i \dot{E}_{x,i} + c_{w,i} \dot{W}_k = c_{q,i} \dot{E}_{x,q,i} + \sum (c_i \dot{E}_i) + Z_k$$

(4)

$$\dot{C}_l = c_l \dot{E}_l$$

(5)

The capital investment cost \((Z_k)\) for each component is calculated using the capital cost equation provided in the literature. The capital cost equations for all components of the cogeneration cycles are presented in part 1 of this paper. For converting the capital investment \((Z_k)\) to capital investment cost rate \((\dot{Z}_k)\) [29]:

$$\dot{Z}_k = \frac{Z_k \cdot CRF \cdot \varphi}{N \times 3600}$$

(6)

where \(\varphi\) is the maintenance factor (1.06) and \(N\) is the number of operating hours per year (7446 h). \(CRF\) is the capital recovery factor and is expressed as [30]:

$$CRF = \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

(7)

where \(i\) is the interest rate and \(n\) is lifetime of the system which are assumed to be 10% and 20 years in this study.

By applying the cost flow rate balance equations and auxiliary equations using \(P\) and \(F\) principals of SPECO approach for each component of the cogeneration cycle, a linear equations system will be resulted. The number of auxiliary equations for each component are equal to \((N_e - 1)\), where \(N_e\) is the number of exiting exergy streams that
are associated with the product definition for that component. The cost rates for all streams of the cogeneration cycle are calculated by solving this linear equations system. After calculating the cost flow rates of each stream, for evaluating the exergoeconomic performance of the cogeneration cycle, the exergoeconomic parameters including the exergoeconomic factor \( f \) and the exergy destruction cost rate \( C_{\dot{D}} \) are defined as:

\[
\dot{C}_{D,k} = c_F k \cdot \dot{E}_{D,k}
\]

\[
f_k = \frac{Z_k}{Z_k + C_{D,k} + C_{L,k}}
\]

where \( \dot{E}_{D,k} \) represents the exergy destruction rate of the component \( k \) defined as:

\[
\dot{E}_D = \sum \dot{E}_{in} - \sum \dot{E}_{out}
\]

\( c_F \) is the average unit cost of fuel exergy of the component \( k \) and \( C_{L,k} \) is the cost rate associated with the exergy loss of the components.

The unit cost of products \( (c_P) \) is equal to the sum of the unit cost of generated power \( (c_w) \) and the unit cost of produced cooling in evaporator \( (c_q) \). The amounts of \( c_w \) and \( c_q \) are obtained from solving the linear equations system of the cogeneration cycle. So, the unit cost of product is defined as:

\[
c_P \ [\$/GJ] = c_w \ [\$/GJ] + c_q \ [\$/GJ]
\]

For the cycles that have more than one product, another parameter called the unit cost of produced exergy can be defined as [31]:

\[
UCOPE \ [\$/GJ] = \frac{\sum \dot{Z}_k + \sum c_F \dot{E}_F}{\sum \dot{E}_P}
\]

where \( \dot{E}_F \) and \( \dot{E}_P \) represent total exergy rate of the input fuels and total exergy rate of products (power and cooling) of the cycle, respectively. Also, \( c_F \) is equal to the unit cost the input fuels of the cycle.

The sum of exergy destruction cost rate and capital investment cost rate of all components of the cogeneration cycle are expressed as:

\[
Objective \ Function = \dot{C}_{D,overall} + \dot{Z}_{overall}
\]

The ratio of the net generated power (electricity) to produced cooling is one of the important parameters in the power and cooling cogeneration cycles. PTQR (power to cooling ratio) parameter is defined as:

\[
PTQR = \frac{W_{net}}{Q_{out}}
\]

In two configurations of simple absorption refrigeration/Kalina cycle, RR parameter is the ratio of the mass flow rate returned from the condenser and the steam generator to the rectifier to the mass flow rate enters the condenser and the steam generator from the rectifier. Also, in the double effect absorption refrigeration/Kalina cycle, the mass flow


rate ratio $(\alpha)$ is defined as:

\[
\alpha = \frac{m_1}{m_2}
\]  

(15)

3. Parametric study

3.1. The double effect absorption refrigeration/Kalina (DEAR/Kalina) cogeneration cycle

In this section, the parametric study of the operating parameters of the double effect absorption refrigeration/Kalina cogeneration cycle is investigated in the specified ranges. The temperature of the high temperature steam generator ($T_{\text{gen1}}$), the temperature of the low temperature steam generator ($T_{\text{gen2}}$), the highest pressure level of the cogeneration cycle ($P_h$), the mass flow rate ratio in the splitter ($\alpha$) and the condenser temperature ($T_{\text{con}}$) are intended as the operating parameters in the double effect absorption refrigeration/Kalina cogeneration cycle. The impacts of these parameters variations have been studied on the thermodynamic and economic performance of the cycle.

Fig. 4 shows the temperature variations of the low temperature steam generator on the first law efficiency and the exergetic economic parameters of the double effect absorption refrigeration/Kalina cogeneration cycle. With increasing the temperature of the low steam temperature, the cost rate values of turbine inlet and outlet streams are decreased. On the other hand, the produced power (electricity) and the capital investment cost rate of the turbine decrease with the increase of the temperature of the low temperature steam generator. So, according to the cost flow rate balance equation for turbine and the variations of the mentioned parameters, as it can be seen, the unit cost of produced power in turbine ($c_w$) will continuously decrease with increasing the temperature of the low temperature steam generator. Also, the trend of unit cost of produced cooling ($c_q$) is justified by the cost flow rate balance equation for the evaporator. The cost rate values for evaporator inlet and outlet streams ($C_{\text{22}}$ and $C_{\text{23}}$), first, decrease with increasing the temperature of the low temperature steam generator, but in the high temperatures of the low temperature steam generator, this trend is reversed. The behavior of the evaporator capital investment cost rate is also the reverse of the $C_{\text{22}}$ and $C_{\text{23}}$ trends. The interaction of these variations in the cost flow rate balance equation for the evaporator is in such a way that the unit cost of cooling has the minimum value at the temperature of the low temperature steam generator about 370 K. As a result, according to the dominance of the unit cost of produced cooling over the unit cost of produced electricity, the unit cost of products ($c_P$) behaves similar to the unit cost of produced cooling, but this parameter has the minimum value at approximately the higher temperature of the low temperature steam generator.

In the double effect absorption refrigeration/Kalina cogeneration
cycle, the highest amounts of the exergy destruction cost rate belong to
the evaporator, the low temperature steam generator and the boiler.
The trends of these components are different with increasing the low
temperature steam generator. The exergy destruction cost rate trends
for evaporator, the low temperature steam generator and the boiler are
the minimum value, ascending and descending behaviors, respectively.
So, the interaction of the exergy destruction cost rate of these compo-
nents is in such a way that the amount of $C_{\text{D,overall}}$ decreases at
first, but

Fig. 8. The effects of simultaneous variations of the temperature of the high temperature steam generator and the high pressure level of the cycle on the performance of DEAR/Kalina
cogeneration cycle.
with further increase of the temperature of the low temperature steam generator, the amount of $C_{D,\text{overall}}$ increases with a high slope. The behavior of overall capital investment cost rate of the cogeneration cycle is a descending trend continuously. So, at the lower temperature of the low temperature steam generator, the overall amount of $C_D + Z$ has a descending trend, but at the higher temperature of the low temperature steam generator, the amount of $C_{D,\text{overall}}$ dominates over the overall capital investment cost rate of the cogeneration cycle and the overall amount of $C_D + Z$ increases with a low slope. Therefore, the value of $C_D + Z$ parameter also has the minimum value at the steam generator temperature of about 370 K. The maximum first law efficiency of this cogeneration cycle occurs at lower temperatures of the low temperature steam generator. At lower temperatures of the low temperature steam generator, the amount of evaporator cooling rate is increased and as a result, the first law efficiency of the overall cogeneration cycle is increased, but with further increase of the temperature of the low temperature steam generator, according to the descending trends of generated electricity and produced cooling in the cogeneration cycle, the amount of first law efficiency is also decreased with a high slope.

The effect of the highest pressure level variation is examined on the first law efficiency and the exergoeconomic parameters of the double effect absorption refrigeration/Kalina cogeneration cycle and is shown in Fig. 5. With the increase of the highest pressure level, all parameters in the cost flow rate balance equation of the evaporator have the descending trends. The interaction of these variations and the balance of input and output cost rates of the evaporator will lead to increase of the unit cost of produced cooling ($c_q$). But the amount of the unit cost of produced power in turbine is continuously decreased with increasing the highest pressure level (the boiler pressure) of the cogeneration cycle. In the lower pressures of the boiler, the amount of the unit cost of produced power dominates over the amount of the unit cost of produced cooling. So, unit cost of products (unit costs of generated electricity and produced cooling) has the descending behavior. But in the higher pressures of the boiler, the increasing slope of the unit cost of produced cooling is increased and as a result, the amount of unit cost of products is also increased. Therefore, it is observed that both the unit cost of produced cooling and unit cost of products are minimized with the increase of the highest pressure of the cogeneration cycle. This specified pressure is an appropriate point for designing of the cycle. As mentioned in the description of the previous figure, the evaporator, the low temperature steam generator and the boiler have the highest values of exergy destruction cost rate among the components of the cogeneration cycle. So, the behaviors of these components have a significant role in the overall exergy destruction cost rate of the cogeneration cycle. The exergy destruction cost rate values of all these components have the descending trends with increasing the highest pressure level of the cogeneration cycle. Also, according to the capital investment cost rate behaviors of the turbine, the third absorber and the low temperature steam generator which have

Fig. 9. The effects of simultaneous variations of the temperature of the low temperature steam generator and $\alpha$ parameter on the performance of DEAR/Kalina cogeneration cycle.
the highest value of the capital investment cost rate among the components of the cogeneration cycle, the behavior of overall capital investment cost rate of the cogeneration cycle is a descending trend. So, the overall amount of $\dot{C}_I + Z$ parameter which is the sum of exergy destruction and capital investment cost rates is continuously decreased. According to the definition of exergoeconomic factor ($f$), the decrease of $\dot{C}_I + Z$ parameter amount will lead to increase of the value of exergoeconomic factor. The amount of net produced electricity of the cogeneration cycle is initially increased slightly with increasing the highest pressure level of the cogeneration cycle, but the more the highest pressure level, the lower the net produced electricity will be obtained. Also, the amount of produced cooling of the cogeneration cycle is continuously decreased with the increase of the highest pressure level of the cogeneration cycle. However, given that the enthalpy difference between the input and output streams of the heat source of the cogeneration cycle (exhaust gasses from diesel engine) decreases with the increase of the highest pressure level of the cogeneration cycle and subsequently the decrease of exergy rate difference between the input and output streams of the heat source, the amounts of the first law efficiency and the second law efficiency are continuously increased.

It can be seen, in the one-dimensional figures, only the changes of one parameter are investigated and the rest of the parameters are fixed. For more comprehensive and better observation of the changes in the thermodynamic and exergoeconomic parameters of the cycles with the operating parameters variations, in this study, it has been tried to present three-dimensional plots in which different behavior of the parameters of the cycle can be observed in different ranges. Sometimes, at the end points of the variation range of a parameter, the behavior of the other parameters is completely different from the behavior of the same parameter at the beginning point of the range, which cannot be seen in the one-dimensional graphs.

Fig. 6 shows the changes in the thermodynamic and exergoeconomic parameters of the double effect absorption refrigeration/Kalina cogeneration cycle with simultaneous variations of the temperature of the low temperature steam generator and the high pressure level of the cycle. As shown in Fig. 6, the unit cost of produced power is continuously reduced with increasing the temperature of the low temperature steam generator. This trend occurs with the increase of the high pressure level of the cycle at low temperatures of the low temperature steam generator. As shown in Fig. 6, the unit cost of produced power is continuously reduced with increasing the temperature of the low temperature steam generator. This trend occurs with the increase of the high pressure level of the cycle at low temperatures of the low temperature steam generator, but at higher temperatures of the low temperature steam generator, the unit cost of produced power reaches the minimum value and then increases. The mentioned behavior occurs for both unit cost of produced cooling and unit cost of the products parameters, but the level of changes of these two parameters will be higher than the changes of the unit cost of produced power with the high pressure level and the temperature of the low temperature steam.
generator variations. Also, $C_D + \dot{Z}$ parameter of the overall cycle has a descending trend with increasing the high pressure level of the cycle, but this parameter is initially decreasing and then will be increased with respect to the low temperature steam generator temperature variation. The behavior of $C_D + \dot{Z}$ parameter is the reverse of the exergy destruction cost rate behavior. Because of the value of the capital investment cost rate in the double effect absorption refrigeration/Kalina cogeneration cycle dominates over the exergy destruction cost rate value, the trend of $C_D + \dot{Z}$ parameter is similar to the capital investment cost rate behavior. The same changes (reach the minimum point and then an ascending trend) are also seen about the value of unit cost of produced exergy with increase of both the low temperature steam generator temperature and high pressure level of the cycle, but the variation of unit cost of produced exergy value is not very high with respect to increase of the high pressure level of the cycle. Also, the amount of first law efficiency increases regularly with increasing the high pressure level of the cycle. At first the increasing slope of the first law efficiency is extremely a lot, but at the higher pressures, this slope reduces. On the other hand, the value of the first law efficiency, with the increase of the low temperature steam generator temperature, reaches the maximum value. The more the temperature of low temperature steam generator, the less amount of the first law efficiency will be obtained. It should be noted that in Fig. 6, the temperature of high temperature steam generator, the mass flow rate ratio and the condenser temperature are assumed to be 453 K, 0.7 and 303.15 K, respectively.

According to Fig. 7, which the simultaneous variations of the temperatures of the low and high temperature steam generators effects are investigated on the thermodynamic and exergoeconomic parameters of the double effect absorption refrigeration/Kalina cogeneration cycle in constant values of the high pressure level of 71.2 bar, the mass flow rate ratio ($\alpha$) of 0.8 and condenser temperature of 303.15 K, The unit cost of produced power at all temperatures of the high temperature steam generator has a decreasing trend. The decreasing slope is high at first, but at the higher temperatures of the high temperature steam generator, this ascending slope will be slight. As regards the amount of unit cost of produced cooling dominates over the value of the unit cost of produced power, the trends of $c_q$ and $c_P$ are similar and in the variation range of the temperature of high temperature steam generator, these two parameters have the minimum value with increasing the temperature of the low temperature steam generator. Interestingly, at low temperatures of the low temperature steam generator, $c_q$ and $c_P$ will have a decreasing trend, but at higher temperatures of the low temperature steam generator, this trend will be reversed. This fact reveals the importance of the simultaneous changes of the parameters and using the three-dimensional figures. The behavior of $C_D + \dot{Z}$ parameter with the increase of the low temperature steam generator temperature is similar to $c_q$ and $c_P$ trends, but this parameter reaches the maximum
value and then decreases with respect to increase of the high temperature steam generator temperature. On the other hand, the unit cost of produced exergy in all range of the temperature of the low temperature steam generator, has an ascending behavior with low slope of changes. Also, as shown in the previous figure, the increase of the low temperature steam generator temperature causes the increase of the first law efficiency of the cycle and reaches its maximum value at 365K and then decreases by increasing the low temperature steam generator temperature.

So far, the changes in the thermodynamic and exergoeconomic parameters of the double effect absorption refrigeration/Kalina cogeneration cycle are investigated with the temperatures of the high and low temperature steam generators and the high pressure level variations. The behaviors were almost determined, but for the study of unusual behaviors such as the $c_q$ and $c_P$ trends with the variations of the temperatures of the high and low steam generators, the changes of the thermodynamic and exergoeconomic parameters of the cogeneration cycle with regard to the simultaneous variations of the temperature of high temperature steam generator as well as the high pressure level of the cycle are shown in Fig. 8. It can be seen, the above mentioned behaviors in the two previous figures with the variations of the high temperature steam generator temperature and the high pressure level, occur with the simultaneous changes of these two parameters and unusual behavior is not observed. Also, $c_P$ parameter has the minimum value with the high pressure level variation, but the range of this change is small and is less than the corresponding change with the high temperature steam generator temperature variation.

The effects of the simultaneous changes of the low temperature steam generator (generator2) temperature and the mass flow rate ratio ($\dot{m_2}$) on the thermodynamic and exergoeconomic parameters of the double effect absorption refrigeration/Kalina cogeneration cycle are shown in Fig. 9. The unit cost of cooling rate and the unit cost of the products have minimum value with the changes of $\alpha$. That means, in the whole range of the low temperature steam generator temperature, in the low values of $\alpha$, the behaviors of $c_q$ and $c_P$ parameters are initially reduced to the minimum value. Then, with increasing $\alpha$, the changes in these two parameters will be ascending. In other words, $c_q$ and $c_P$ parameters have the minimum value with respect to the simultaneous variations of $\alpha$ and temperature of the low temperature steam generator, which is very important in the design of this cycle. The amount of the other important economic parameter ($C_P + Z$) with increasing the value of $\alpha$ is a descending trend with the fact that at lower temperatures of steam generator2, this decreasing slope is a lot, but at higher temperatures of steam generator2, this slope declines. Also, the capital investment cost rate and unit cost of produced exergy will be
increased with rising the value of $\alpha$. These changes in the higher temperature of the low temperature steam generator are very low which seems like a straight line. As previously mentioned, the capital investment cost rate and unit cost of produced exergy parameters have the minimum value with the change of the temperature of the low temperature steam generator, which is repeated throughout the $\alpha$ variation range. On the other hand, the values of the first law and second law efficiencies will also increase with the increment of $\alpha$ value, and the highest amount of these efficiencies will be occurred at the highest $\alpha$ value. But the change behavior of the exergy destruction rate with the change of $\alpha$ is the reverse of the thermodynamic efficiency and will have a descending trend.

3.2. The first configuration of the simple absorption refrigeration/Kalina (SAR/Kalina) cogeneration cycle

The steam generator temperature ($T_{\text{gen}}$), high pressure level of the cogeneration cycle ($P_h$), RR parameter and the condenser temperature ($T_{\text{cond}}$) are considered as the operating parameters in the first configuration of the simple absorption refrigeration/Kalina cogeneration cycle. In Fig. 10, the effects of the simultaneous changes of the steam generator temperature and the high pressure level of the cycle are examined on the thermodynamic and exergoeconomic parameters of the first configuration of the simple absorption refrigeration/Kalina cogeneration cycle. It is observed that the behavior of the unit cost of products is exactly the same as the behaviors of the unit cost of power and the unit cost of cooling. In this way, in whole range of the high pressure level variations, the amounts of these parameters decline with increasing the generator temperature. The decreasing slope is considerable at the lower steam generator temperature, but the more steam generator temperature, the less decreasing slope will be, which at the end range of the steam generator temperature reaches the minimum. Also, at all generator temperatures, the variation of the unit cost of products has the minimum value regarding the high pressure level of the cycle changes. The remarkable point is that the higher the steam generator temperature, the lower value of the unit cost of products will be happened at the higher pressure levels. Moreover, $C_0 + Z$ parameter has a descending behavior regarding the increment of both steam generator temperature and pressure level of the cycle. The lowest value for this parameter occurs at the highest amounts of the steam generator temperature and pressure level of the cycle. Also, the unit cost of produced exergy has the minimum value with regard to both steam generator temperature and the pressure level simultaneous variations. The

Fig. 11. The effects of simultaneous variations of the steam generator temperature and RR parameter on the performance of first configuration of SAR/Kalina cogeneration cycle.
more the steam generator temperature, the lower the unit cost of produced exergy will be, which is the reverse trend occurred for the unit costs of the product. The PTQR parameter, which indicates the amount of net produced power to the cooling rate produced in the evaporator, has the slight changes with the steam generator temperature variations, but with increasing the high pressure level of the cycle, it initially increases with a high slope and reaches the maximum value in the end amount of the pressure level range. The first law efficiency trend is exactly the opposite of the $C_0 + Z$ parameter behavior and will have a completely increasing behavior with the increment of both the steam generator temperature and the high pressure of the cycle. The highest value of the first law efficiency will occur at the highest amounts of the steam generator temperature and the boiler pressure.

The effects of the simultaneous changes of the steam generator temperature and RR parameter on the thermodynamic and exergoeconomic parameters of the first configuration of the simple absorption refrigeration/Kalina cogeneration cycle are shown in Fig. 11. It can be seen, the behaviors of the unit cost of products, the unit cost of produced power and the unit cost of produced cooling parameters are similar. These parameters, with increasing the value of RR parameter, will have a completely incremental behavior and will decrease with increase of the steam generator temperatures. The trend of $C_0 + Z$ parameter is similar to the unit cost of products trend with respect to both RR parameter and steam generator temperature changes with the difference that the decreasing slope of $C_0 + Z$ parameter regarding the steam generator temperature is greater and this reduction will be continued in all variation range of the steam generator temperature. Also, the unit cost of produced exergy has the minimum value with regard to the steam generator temperature variations. Throughout the range of RR variations, this minimum point is approximately occurred in the specific temperature of the steam generator. The more the value of RR parameter, the more amount of the unit cost of produced exergy will be. The exergoeconomic factor and first law efficiency behaviors, inverse of all economic parameters trends such as $c_P$, $UCOPE$ and $C_0 + Z$, will decrease with increasing the RR parameter value. Therefore, it is generally seen that at the lowest value of RR parameters, the lowest amount of costs and the highest thermodynamic efficiency value will be achieved.

The effects of changes in high pressure level of the cycle and RR parameter on the energy, exergy and economic performance of the first configuration of the simple absorption refrigeration/Kalina cogeneration cycle are explained separately in two previous figures, but for the better understanding of the subject and the process of the changes, the effects of the simultaneous changes of these two parameters are shown in Fig. 12. In this figure, the effects of changes in the parameters that will be considered as the objective functions in the optimization section
are discussed.

The condenser temperature is very effective in designing the considered cycle, because the steam generator and rectifier pressure is determined through the operating temperature of the condenser. So, in Fig. 13, the simultaneous changes of the steam generator and condenser temperatures effects are investigated on the thermodynamic and exergoeconomic parameters of the first configuration of the simple absorption refrigeration/Kalina cogeneration cycle. The unit cost of
Fig. 13. The effects of simultaneous variations of the steam generator temperature and condenser temperature on the performance of first configuration of SAR/Kalina cogeneration cycle.
products has an ascending trend with the increase of the condenser temperature. The ascending slope is a lot at the low steam generator temperatures, but at higher temperatures of the steam generator, this slope declines and the unit cost of products behavior is similar to a straight line. The same trend is repeated in the unit cost of produced exergy and $C_Z$ parameters with the difference that the ascending slope of $C_Z$ parameter in whole steam generator temperature range is almost constant and changes very little. It is also observed that the increase of the condenser temperature decreases the first law efficiency value, but the rate of first law efficiency changes regarding the condenser temperature variations is less than the rate of corresponding changes with the steam generator temperature changes, which is apparent in the Fig. 13. Therefore, the maximum value of the first law efficiency occurs at the lowest value in the range of the condenser temperature changes. According to the Fig. 13, it is evident that at low temperatures of the steam generator, with increasing the condenser temperature, the amount of exergoeconomic factor will be increased, but at higher temperatures of the steam generator, this trend will be reversed and in some parts, it is constant and in another part, a descending trend will be found.

3.3. The second configuration of the simple absorption refrigeration/Kalina (SAR/Kalina) cogeneration cycle

Like the first configuration, the steam generator temperature, high pressure level of the cogeneration cycle, RR parameter and the condenser temperature are considered as the operating parameters in the second configuration of the simple absorption refrigeration/Kalina cogeneration cycle.

In Fig. 14, the effects of the simultaneous changes of the steam generator temperature and the high pressure level of the cycle are studied on the thermodynamic and exergoeconomic parameters of the second configuration of the simple absorption refrigeration/Kalina cogeneration cycle. It can be seen that the parameters of the unit cost of products and the unit cost of produced power and cooling parameters have the same behavior with regard to the changes in the steam generator temperature and the high pressure level, so that in whole range of the steam generator temperature variations, these parameters have minimum values regarding the changes of high pressure level of the cycle. It is worth noting that the more the steam generator temperature, the minimum values of these three parameters will be occurred at the lower pressure level. It can also be seen that all $C_w$, $C_q$ and $C_P$ parameters, with increasing the steam generator temperature, first begin to decrease with a large slope, but at higher steam generator temperature this slope

![Fig. 14. The effects of simultaneous variations of the steam generator temperature and the high pressure level on the performance of second configuration of SAR/Kalina cogeneration cycle.](image)
decreases. At the end value of the steam generator temperature range, the amounts of these three parameters are minimized. The same trend is also valid for $C_0 + Z$ parameter; with the difference that the minimum values of this parameter will be occurred at higher pressure levels than the minimum amount of $c_P$. The behavior of the unit cost of produced power is equal to $C_0 + Z$ parameter trend with respect to the steam generator temperature and the boiler pressure variations. On the other hand, the amount of exergoeconomic factor of the cogeneration cycle has the maximum point with the changes in the boiler pressure in the way that, at first, in lower value of the boiler pressure, the $f$ value is ascending and reaches the maximum value, and then will be in a descending trend with further increase of the boiler pressure. Also, the behavior of exergoeconomic factor will be ascending with increasing the steam generator temperature. The changes slope will first be a lot, but at higher steam generator temperatures, the slope of this change will be declined. The same behavior of the exergoeconomic factor occurs almost for the first law efficiency changes with the steam generator temperature and boiler pressure variations, except that the minimum values of the first law efficiency occurs at relatively high boiler pressures. Also, the exergy destruction rate has the same behavior of $C_0 + Z$ parameter, which implies that the cost rate associated with exergy destruction is surrounded by the capital investment cost rate of the components.

The effects of the simultaneous variations of the high pressure level (boiler pressure) and RR parameter on the thermodynamic and exergoeconomic parameters of the second configuration of the simple absorption refrigeration/Kalina cogeneration cycle are presented in Fig. 15. It is evident that $c_w$, $c_q$ and $c_P$ parameters have the minimum values regarding both the boiler pressure and RR parameter variations. In all range of the boiler pressure variations, the values of these three parameters are initially decreased with increasing the RR value and reach the minimum values, then at the more values of RR, the amount of these three parameters will be decreased. At all pressure levels of the cycle, there are the minimum values of these three parameters at approximately a specific amount of RR. The changes for $c_w$, $c_q$ and $c_P$ parameters regarding the boiler pressure and RR parameter changes are also observed for $C_0 + Z$ parameter, with the difference that, firstly, the minimum value of $C_0 + Z$ happens at lower values of RR parameter, and secondly, the variation slope of $C_0 + Z$ parameter with the change of the boiler pressure is much higher than corresponding value with the RR parameter changes. The amount of unit cost of the produced exergy will absolutely increase with the increase of the RR parameter value, and the lowest amount of the unit cost of produced exergy will be occurred at the lowest value of the RR range. The interesting point in this figure is that the same behavior can be seen about the first law efficiency which is a thermodynamic parameter with the exergoeconomic factor parameter which is an economic parameter, regarding the simultaneous variations of the boiler pressure and RR parameter. These
parameters have the maximum values with increasing both the boiler pressure and RR parameter. The behavior of overall exergy destruction rate of the cycle is the same as the behavior of $C_D + Z$ parameter. Of course, the variation slope of exergy destruction rate with respect to both the boiler pressure and RR parameter is close to each other, which results in a smoother plot.

For a better understanding and the presence or absence of unusual behavior in the parameters, the effects of the simultaneous variations of the steam generator temperature and RR parameter are investigated on the thermodynamic and exergoeconomic parameters of the second configuration of the simple absorption refrigeration/Kalina cogeneration cycle and are shown in Fig. 16. The simultaneous study of these two parameters (the variations of these parameters are examined separately in two previous figures) gives us a better view of the considered cogeneration cycle analysis in all range of these two parameters variations.

As already mentioned, the condenser temperature creates one of the pressure levels of the considered cogeneration cycles. The changes in the condenser temperature and, subsequently, the variations in the operating pressure of the components available at this pressure level will certainly have a significant effect on the thermodynamic and exergoeconomic performance of the considered cogeneration cycles. Therefore, in Fig. 17, the simultaneous variations of the condenser temperature and the steam generator temperature effects are examined on the important thermodynamic and exergoeconomic parameters of the second configuration of the simple absorption refrigeration/Kalina cogeneration cycle. It can be observed that the behaviors of the unit cost of products and $C_D + Z$ parameters will be different with respect to the increase of the condenser temperature. At lower steam generator temperatures, the value of these two parameters increase with increasing the condenser temperature. With more increase of the steam generator temperature, the increasing trend of these two parameters will be moderated regarding the increase of the condenser temperature. Finally, at high steam generator temperatures, this behavior will be completely reversed and will have an entirely descending trend.

It is also necessary to note that the variation of the unit cost of products and $C_D + Z$ parameters with the condenser temperature changes will be less than the variations of these two parameters regarding the steam generator temperature changes. However, in the case of other important parameters including the unit cost of produced exergy and the first law efficiency, the mentioned trends are not observed. In all range of the steam generator temperature variations, the behavior of these two parameters will be a completely ascending trend regarding the increase of the condenser temperature. The lowest value of the unit cost of produced exergy and the highest amount of the first law efficiency will be occurred in the lowest and highest values of the condenser temperature in the condenser temperature variations range, respectively.
4. Optimization

For a more comprehensive comparison of the considered cogeneration cycles, these cycles have been optimized. The optimization is done using direct search method in the EES software by a direct search algorithm known as Powell’s method [32]. For the considered cogeneration cycles, the decision parameters along with the range of variations of each parameter for the optimization are as follows:

Double effect absorption refrigeration/Kalina (DEAR/Kalina) cogeneration cycle:

\[\begin{align*}
410 < T_{g1} < 460 & \quad 360 < T_{g2} < 390 & \quad 50 < P_h < 140 & \quad 0.4 < \alpha < 0.8 \\
303 < T_{cond} < 320
\end{align*}\]

First configuration of simple absorption refrigeration/Kalina (SAR/Kalina) cogeneration cycle:

\[\begin{align*}
410 < T_{g1} < 460 & \quad 50 < P_h < 140 & \quad 0.15 < RR < 0.4 & \quad 303 < T_{cond} < 320
\end{align*}\]

Second configuration of simple absorption refrigeration/Kalina (SAR/Kalina) cogeneration cycle:

\[\begin{align*}
410 < T_{g1} < 460 & \quad 35 < P_h < 90 & \quad 0.15 < RR < 0.4 & \quad 303.15 < T_{cond} < 320.15
\end{align*}\]

The unit cost of products, first law efficiency, second law efficiency and unit cost of produced exergy as well as the sum of exergy destruction cost rate and capital investment cost rate are considered as the five objective functions in this study. The obtained results from optimizing the considered cogeneration cycles have been shown in Tables 1–3.

According to the obtained results of optimization, the superiority of DEAR/Kalina cogeneration cycle is clearly apparent from the thermodynamic viewpoint, but the first and second configurations of SAR/Kalina cogeneration cycles are in a much better situation from the exergoeconomic viewpoint compared with DEAR/Kalina cogeneration cycle. Among the considered cogeneration cycles, the maximum values of the first and second law efficiencies belong to DEAR/Kalina cogeneration cycle with 44.96% and 60.62%, respectively. The first law efficiency value of DEAR/Kalina cogeneration cycle in maximum energy efficiency optimum state is 13.89%point and 21.44%point more than the corresponding values for the first and second configurations of SAR/Kalina cycles, respectively. Also, in maximum exergy efficiency optimum state, the second law efficiency value of DEAR/Kalina cogeneration cycle is 5.82%point and 17.36%point more than the second law efficiency values of the first and second configurations of SAR/Kalina cycles, respectively. For the DEAR/Kalina cogeneration cycle, in the case of maximum first law efficiency optimum state, the amounts of \(c_v\), second law efficiency, UCOPE and \(C_D + Z\) are obtained 240.86($/GJ), 57.46%, 15.04($/GJ) and 10.79($/h) which are different with the optimum amounts of these parameters. The optimum values of \(c_v\), second law efficiency, UCOPE and \(C_D + Z\) are 165.42($/GJ), 60.62%, 8.176($/GJ) and 8.118($/h) for the DEAR/Kalina cogeneration cycle.
optimum values of these parameters are 138.18($/GJ), 54.8%, 5.947($/GJ) and 5.429($/h), respectively, for the first configuration of SAR/Kalina cogeneration cycle and 152.3($/GJ), 43.26%, 6.107($/GJ) and 7.574($/h), respectively, for the second configuration of SAR/Kalina cogeneration cycle. So, it can be seen the amounts of thermodynamic and exergoeconomic parameters of the studied cogeneration cycles are different in optimum states. These differences are very important in designing these cogeneration cycles.

Reverse of the thermodynamic behavior of the considered cogeneration cycles, the economic performance of the cycles indicates the predominance of the first and second configurations of SAR/Kalina cycles over the DEAR/Kalina cycle. All minimum values of the unit cost of products, unit cost of produced exergy as well as the sum of exergy destruction and capital investment cost rates belong to the first configuration of SAR/Kalina cogeneration cycle in optimum state while both the first and second law efficiencies in this cycle was less than the DEAR/Kalina cycle that is very interesting result. Even the values of the unit cost of products, unit cost of produced exergy as well as the sum of exergy destruction and capital investment cost rates for the second configuration of SAR/Kalina cogeneration cycle in optimum state (which are 152.3($/GJ), 6.107($/GJ) and 7.574($/h), respectively) are less than the corresponding values for the DEAR/Kalina cycle in which these optimum parameters are 165.42($/GJ), 8.176($/GJ) and 8.118($/h), respectively. Therefore, only the high amounts of the first and second law efficiencies of the cycle is not the reason for priority of the cycle and regarding the obtained results of optimization, the cogeneration cycle with the lower values of the first and second law efficiencies, has far more favorable economic performance than other cogeneration cycles.

In the minimum unit cost of products optimum state, the \( c_P \) value of the first configuration of SAR/Kalina cogeneration cycle is 16.46% and 9.27% less than the corresponding value for the DEAR/Kalina cycle and second configuration of SAR/Kalina cycle, respectively. Also, the minimum value of \( c_P \) for the second configuration of SAR/Kalina cogeneration cycle is 7.93% less than the corresponding value for the DEAR/Kalina cogeneration cycle and 10.22% more than the corresponding value for the first configuration of SAR/Kalina cogeneration cycle.

The value of the other important exergoeconomic parameter \( \frac{\hat{C}_\theta + \hat{Z}}{\hat{C}_D} \) for the first configuration of SAR/Kalina cogeneration cycle in optimum state (5.429 $/h) is 28.32% and 33.12% less than the corresponding values for SAR/Kalina cycle and DEAR/Kalina cycle, respectively. Also, the minimum value of \( \frac{\hat{C}_\theta + \hat{Z}}{\hat{C}_D} \) for the second configuration of SAR/Kalina cogeneration cycle in optimum state (7.574 $/h) is 6.7% less than the corresponding value for the DEAR/Kalina cycle. So, it is clear that the way of combination of power and refrigeration cycles for creating the cogeneration cycle is very influential on the economic performance of cogeneration cycle, because it is observed that the way of combination of power and refrigeration cycles for creating the cogeneration cycle is very influential on the economic performance of cogeneration cycle.
of combination of Kalina cycle and simple absorption refrigeration cycle leads to different exergoeconomic results for two different configurations of absorption refrigeration/Kalina cogeneration cycle. It is worth noting that the cycles can be taken into considerations that have a satisfactory performance from all energy, exergy and economic viewpoints.

On the other hand, it’s observed that in different considered optimum states, the amounts of operating parameters in all considered cogeneration cycle are different that can be provided several conditions for designing these cogeneration cycles to implement the desired purposes. For example, in minimum value of the unit cost of products optimum state in DEAR/Kalina cogeneration cycle, the first law efficiency (43.73%) is 1.23% point less than the first law efficiency value of DEAR/Kalina cycle in maximum first law efficiency optimum state (44.96%). These differences are available for all considered cogeneration cycles and are clearly presented in Tables 1–3. Also, the summary of the optimization results is shown in Fig. 18.

To evaluate the economic situation of the considered cogeneration cycles, these cycles are compared with the Goswami cycle in the same heat source condition. The comparison is done in the optimum states and the results are shown in Table 4. It can be seen the considered power and cooling cogeneration cycles have the better performance compared to the Goswami cycle from both the energy and exergoeconomic viewpoints. In the same heat source condition, the maximum first law efficiency of Goswami cycle is less than the corresponding values for all studied cogeneration cycles based on Kalina with a great difference. On the other hand, the exergoeconomic performance of the studied cogeneration cycles is much better than the Goswami cycle. The minimum values of unit cost of products for the double effect absorption refrigeration/Kalina and two configurations of simple absorption refrigeration/Kalina cogeneration cycles are 4.71%, 20.4% and 12.27%, respectively, less than the corresponding value for the Goswami cycle. In the case of unit cost of produced exergy optimum state, the minimum values of the unit cost of produced exergy for the studied cogeneration cycles are 2.15%, 28.82% and 26.91%, respectively, less than the corresponding value for the Goswami cycle. Also, the minimum values of $C_0 + Z$ parameter for all studied cogeneration cycles are less than the value of this parameter for the Goswami cycle. So, according to the Table 4, the superiority of the power and cooling cogeneration cycles based on Kalina is observed compared to the conventional power and cooling cogeneration cycles such as Goswami cycle in terms of energy, exergy and exergoeconomics.

5. Payback period

Another important parameter in the economic analysis of energy conversion systems is the payback period (PP) parameter, which determines the time taken to recover the capital expenditure for the purchase of components, installation and maintenance of the system. The system with the low amount of payback period is more desirable.
The effects of simultaneous variations of the steam generator temperature and condenser temperature on the performance of second configuration of SAR/Kalina cogeneration cycle.

**Table 1**
The obtained optimization results of DEAR/Kalina cogeneration cycle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum of $c_P$</th>
<th>Maximum of the first law efficiency</th>
<th>Maximum of the second law efficiency</th>
<th>Minimum of UCOPE</th>
<th>Minimum of $Q_{overall} + Z_{overall}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{gen1}$ [K]</td>
<td>460</td>
<td>410</td>
<td>410</td>
<td>410</td>
<td>410</td>
</tr>
<tr>
<td>$T_{gen2}$ [K]</td>
<td>374.8</td>
<td>367.2</td>
<td>360</td>
<td>386.2</td>
<td>376.9</td>
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<tr>
<td>$p_c$ [bar]</td>
<td>113.6</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>$\alpha$ [-]</td>
<td>0.59</td>
<td>0.8</td>
<td>0.8</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>$T_{cond}$ [K]</td>
<td>305.4</td>
<td>310.7</td>
<td>303.15</td>
<td>307.4</td>
<td>303.15</td>
</tr>
<tr>
<td>$c_P$ [$/GJ$]</td>
<td>165.42</td>
<td>240.86</td>
<td>211.28</td>
<td>200.25</td>
<td>216.5</td>
</tr>
<tr>
<td>First law efficiency [%]</td>
<td>43.73</td>
<td>44.96</td>
<td>44.63</td>
<td>43.83</td>
<td>43.83</td>
</tr>
<tr>
<td>Second law efficiency [%]</td>
<td>55.14</td>
<td>57.46</td>
<td>60.62</td>
<td>55.3</td>
<td>55.3</td>
</tr>
<tr>
<td>$c_w$ [$/GJ$]</td>
<td>31.82</td>
<td>28.56</td>
<td>28.98</td>
<td>22.6</td>
<td>26.25</td>
</tr>
<tr>
<td>$c_q$ [$/GJ$]</td>
<td>133.6</td>
<td>212.3</td>
<td>182.3</td>
<td>193.9</td>
<td>174</td>
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<tr>
<td>$c_{D_{overall}} + Z_{overall}$ [$$/h]</td>
<td>9.56</td>
<td>10.79</td>
<td>8.846</td>
<td>10.429</td>
<td>8.118</td>
</tr>
<tr>
<td>$c_{D_{overall}}$ [$$/h]</td>
<td>7.049</td>
<td>6.723</td>
<td>5.442</td>
<td>5.938</td>
<td>6.63</td>
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<tr>
<td>$Z_{overall}$ [$$/h]</td>
<td>2.511</td>
<td>4.067</td>
<td>3.404</td>
<td>2.15</td>
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<td>$E_{D_{overall}}$ [kW]</td>
<td>80.29</td>
<td>71.35</td>
<td>68.01</td>
<td>68.74</td>
<td>64.75</td>
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<tr>
<td>$W_Y$ [kW]</td>
<td>70.01</td>
<td>75.21</td>
<td>79.06</td>
<td>58.93</td>
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<tr>
<td>$Q_{out}$ [kW]</td>
<td>161.3</td>
<td>127.4</td>
<td>135.3</td>
<td>128.6</td>
<td>129.5</td>
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<tr>
<td>$f_{overall}$ [%]</td>
<td>26.25</td>
<td>37.69</td>
<td>38.48</td>
<td>26.85</td>
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<tr>
<td>PTQR</td>
<td>0.4151</td>
<td>0.5491</td>
<td>0.5541</td>
<td>0.4366</td>
<td>0.4798</td>
</tr>
</tbody>
</table>
from the economic viewpoint. The payback period parameter is defined as [33]:

\[
PP = \frac{C_{TDE}}{ANSF}
\]

(16)

where \(C_{TDE}\) is the capital expenditure for the purchase of components, installation and maintenance the system in dollars, and is obtained from the following:

\[
C_{TDE} = Z_{overall} \cdot \phi
\]

(17)

\(Z_{overall}\) is the total capital investment cost rate of the components of the cycle and \(\phi\) is the maintenance factor. Also, the amount of \(ANSF\) parameter is expressed as:

\[
ANSF = 0.1/($/kWh) \dot{W}/(kW) \cdot N \cdot (h/year)
\]

(18)

where 0.1 ($/kWh) is equal to the selling price of produced electricity of the system [34] and \(N\) is the number of operating hours per year (7446 h). In this study, because of the power and cooling are produced simultaneously in the cogeneration cycles, the cooling value is converted to the minimum power to produce it by the coefficient of performance of the absorption refrigeration cycle.

The payback period for the considered cogeneration cycles in different optimum state is calculated and shown in Figs. 19–23. In these figures, the unit of the values is year.

According to Figs. 19–23, it can be observed that in all optimum states except for the minimum unit cost of produced exergy, the first configuration of SAR/Kalina cycle has the lowest amount of payback period among the considered cogeneration cycle. Therefore, the better performance of this cycle from the economic viewpoint is evident as seen in the previous section. But the remarkable point is that, in the maximum first and second law efficiencies optimum states, the payback period for the DEAR/Kalina cogeneration cycle is the highest value among the considered cogeneration cycles while the highest amount of first and second law efficiencies belong to the DEAR/Kalina cogeneration cycle with a great difference. So, the more desirable performance of the first configuration of SAR/Kalina cycle among the considered cycles is obvious.

Also, a NPV analysis is done on the considered cogeneration cycles based on Kalina. NPV (Net Present Value) is the difference between the present value of cash inflows and the present value of cash outflows.

### Table 2

The obtained optimization results of the first configuration of SAR/Kalina cogeneration cycle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum of (c_P)</th>
<th>Maximum of the first law efficiency</th>
<th>Maximum of the second law efficiency</th>
<th>Minimum of UCOPE</th>
<th>Minimum of (Q_{overall} + Z_{overall})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_{gen}) [K]</td>
<td>457.6</td>
<td>460</td>
<td>460</td>
<td>452.8</td>
<td>460</td>
</tr>
<tr>
<td>(P_a) [bar]</td>
<td>118.7</td>
<td>140</td>
<td>140</td>
<td>103.65</td>
<td>140</td>
</tr>
<tr>
<td>RR [-]</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>(T_{cond}) [K]</td>
<td>303.15</td>
<td>303.15</td>
<td>303.15</td>
<td>303.15</td>
<td>303.15</td>
</tr>
<tr>
<td>(c_P) [$/GJ]</td>
<td>138.18</td>
<td>138.52</td>
<td>138.52</td>
<td>138.03</td>
<td>138.52</td>
</tr>
<tr>
<td>First law efficiency [%]</td>
<td>30.4</td>
<td>31.07</td>
<td>31.07</td>
<td>29.79</td>
<td>31.07</td>
</tr>
<tr>
<td>Second law efficiency [%]</td>
<td>54.13</td>
<td>54.8</td>
<td>54.8</td>
<td>53.49</td>
<td>54.8</td>
</tr>
<tr>
<td>(c_e) [$/GJ]</td>
<td>31.88</td>
<td>31.97</td>
<td>31.97</td>
<td>31.02</td>
<td>31.97</td>
</tr>
<tr>
<td>(c_i) [$/GJ]</td>
<td>106.3</td>
<td>106.55</td>
<td>106.55</td>
<td>107</td>
<td>106.55</td>
</tr>
<tr>
<td>(Q_{overall} + Z_{overall}) [$/h]</td>
<td>5.745</td>
<td>5.426</td>
<td>5.426</td>
<td>6.002</td>
<td>5.429</td>
</tr>
<tr>
<td>(Z_{overall}) [$/h]</td>
<td>4.364</td>
<td>4.095</td>
<td>4.095</td>
<td>4.581</td>
<td>4.095</td>
</tr>
<tr>
<td>(Z_{overall}) [$/h]</td>
<td>1.381</td>
<td>1.334</td>
<td>1.334</td>
<td>1.421</td>
<td>1.334</td>
</tr>
<tr>
<td>(c_{UOEPE}) [$/GJ]</td>
<td>54.22</td>
<td>50.76</td>
<td>50.76</td>
<td>57.23</td>
<td>50.76</td>
</tr>
<tr>
<td>(W_f) [kW]</td>
<td>65.2</td>
<td>62.67</td>
<td>62.67</td>
<td>67.1</td>
<td>62.67</td>
</tr>
<tr>
<td>(Q_{ex}) [kW]</td>
<td>18.33</td>
<td>17.35</td>
<td>17.35</td>
<td>19.08</td>
<td>17.35</td>
</tr>
<tr>
<td>(f_{overall}) [%]</td>
<td>24.04</td>
<td>24.57</td>
<td>24.57</td>
<td>23.67</td>
<td>24.57</td>
</tr>
<tr>
<td>PTQR</td>
<td>3.472</td>
<td>3.514</td>
<td>3.514</td>
<td>3.441</td>
<td>3.514</td>
</tr>
</tbody>
</table>

### Table 3

The obtained optimization results of the second configuration of SAR/Kalina cogeneration cycle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum of (c_P)</th>
<th>Maximum of the first law efficiency</th>
<th>Maximum of the second law efficiency</th>
<th>Minimum of UCOPE</th>
<th>Minimum of (Q_{overall} + Z_{overall})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_{gen}) [K]</td>
<td>456.6</td>
<td>460</td>
<td>460</td>
<td>460</td>
<td>456.1</td>
</tr>
<tr>
<td>(P_a) [bar]</td>
<td>52.36</td>
<td>48.6</td>
<td>51.8</td>
<td>72.7</td>
<td>72.35</td>
</tr>
<tr>
<td>RR [-]</td>
<td>0.344</td>
<td>0.337</td>
<td>0.326</td>
<td>0.15</td>
<td>0.37</td>
</tr>
<tr>
<td>(T_{cond}) [K]</td>
<td>320.15</td>
<td>320.15</td>
<td>320.15</td>
<td>303.15</td>
<td>307.4</td>
</tr>
<tr>
<td>(c_P) [$/GJ]</td>
<td>152.3</td>
<td>153.67</td>
<td>153.67</td>
<td>158.3</td>
<td>156.5</td>
</tr>
<tr>
<td>First law efficiency [%]</td>
<td>23.24</td>
<td>23.52</td>
<td>23.52</td>
<td>22.54</td>
<td>22.4</td>
</tr>
<tr>
<td>Second law efficiency [%]</td>
<td>43.04</td>
<td>43.22</td>
<td>43.26</td>
<td>42.34</td>
<td>42.06</td>
</tr>
<tr>
<td>(c_e) [$/GJ]</td>
<td>34.52</td>
<td>34.37</td>
<td>35.37</td>
<td>35.31</td>
<td>35.36</td>
</tr>
<tr>
<td>(c_i) [$/GJ]</td>
<td>117.8</td>
<td>119.3</td>
<td>118.3</td>
<td>123</td>
<td>121.1</td>
</tr>
<tr>
<td>(Z_{overall}) [$/h]</td>
<td>6.323</td>
<td>6.32</td>
<td>6.285</td>
<td>6.7</td>
<td>6.251</td>
</tr>
<tr>
<td>(Z_{overall}) [$/h]</td>
<td>1.394</td>
<td>1.401</td>
<td>1.393</td>
<td>1.303</td>
<td>1.323</td>
</tr>
<tr>
<td>(c_{UOEPE}) [$/GJ]</td>
<td>7.717</td>
<td>7.721</td>
<td>7.678</td>
<td>8.003</td>
<td>7.574</td>
</tr>
<tr>
<td>(W_f) [kW]</td>
<td>80.41</td>
<td>80.09</td>
<td>79.74</td>
<td>81.25</td>
<td>82.29</td>
</tr>
<tr>
<td>(Q_{ex}) [kW]</td>
<td>13.19</td>
<td>13.28</td>
<td>13.12</td>
<td>12.26</td>
<td>12.32</td>
</tr>
<tr>
<td>(f_{overall}) [%]</td>
<td>18.27</td>
<td>18.14</td>
<td>18.14</td>
<td>16.28</td>
<td>17.47</td>
</tr>
<tr>
<td>PTQR</td>
<td>4.526</td>
<td>4.51</td>
<td>4.51</td>
<td>4.551</td>
<td>4.775</td>
</tr>
</tbody>
</table>
over a period of time. NPV is used to analyze the profitability of a project. Regarding the studied cogeneration cycles are used for heat recovery from the diesel engine exhaust gases, the only cash outflow is related to the capital expenditure for the purchase of components, installation and maintenance of the system. So, the cost of fuel in the considered cogeneration cycles is zero. NPV is defined as:

\[ NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + i)^t} - C_0 \]  \hspace{1cm} (19)

where \( C_t \) is the net cash inflow during the time period, \( C_0 \) is total initial investment costs, \( i \) is the discount rate and \( T \) is the number of time periods in year. According to the above descriptions, NPV for the

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**Table 4**
The comparison of the studied cogeneration cycles with the Goswami cycle with the same heat source condition.

<table>
<thead>
<tr>
<th>Cogeneration cycles</th>
<th>Minimum of ( c_p ) ($/GJ)</th>
<th>Minimum of ( UCOPE ) ($/GJ)</th>
<th>Minimum of ( C_0 + 2 ) ($/h)</th>
<th>Maximum of first law efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goswami</td>
<td>173.6</td>
<td>8.356</td>
<td>9.879</td>
<td>14.73</td>
</tr>
<tr>
<td>DEAR/Kalina</td>
<td>165.42</td>
<td>8.176</td>
<td>8.118</td>
<td>44.96</td>
</tr>
<tr>
<td>First configuration of SAR/Kalina</td>
<td>138.18</td>
<td>5.947</td>
<td>5.429</td>
<td>31.07</td>
</tr>
<tr>
<td>Second configuration of SAR/Kalina</td>
<td>152.3</td>
<td>6.107</td>
<td>7.574</td>
<td>23.52</td>
</tr>
</tbody>
</table>

---

**Fig. 18.** The summary of the optimization results obtained for the considered cogeneration cycles.

**Fig. 19.** The payback period in minimum unit cost of products optimum state.

**Fig. 20.** The payback period in maximum first law efficiency optimum state.

**Fig. 21.** The payback period in maximum second law efficiency optimum state.
The overall capital investment cost in each year. So, the value of \( \gamma \)
coefficient in the Eq. (20) is considered 0.06. Also, the values of \( i \) and \( N \)
are assumed to be 10% and 20 years. A positive net present value indicates that the
projected earnings generated by a project or investment (in present dollars) exceed the anticipated costs (also in present dollars). Generally, a project with a positive NPV will be a profitable project and a project with a negative NPV will result in a net loss. This concept is the basis for the net present value rule, which dictates that the only investments that should be made are those with positive NPV values. The calculated NPV for the studied cogeneration cycles in all considered optimum states are shown in Fig. 24. It is observed that net present values (NPV) for the studied cogeneration cycles in all considered optimum states are positive and the all studied cogeneration cycles are the profitable projects. The profitability of the studied cogeneration cycles are also shown in the payback period analysis.

Another parameter for economic comparison of the systems is the internal rate of return (IRR) which is a method of calculating rate of return. Internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. So the internal rate of return is calculated as \( NPV (i^*, T) = 0 \) in which \( i^* \) is the internal rate of return. The use of internal refers to the omission of external factors such as the cost of capital or inflation, from the calculation. The values of IRR for the studied cogeneration cycles are presented in Fig. 25.

The reason of the high value of IRR for the studied cogeneration cycles is in one hand, these cogeneration cycles are used for heat recovery from the diesel engine exhaust gases. So, the cost of fuel during the operating period of the system is zero. The only cash outflow of the system belongs to the capital expenditure for the purchase of components, installation and maintenance of the system. So, this subject will lead to high value of IRR for the studied cogeneration cycle. On the other hand, according to the operating period of the system (20 years) and the simultaneous production of power and cooling, both the thermodynamic efficiency and internal rate of return values are obtained high for the cogeneration systems. Therefore, it is observed that both the thermodynamic efficiency and internal rate of return values for the cogeneration cycles is much higher than the corresponding values for separate usual power cycle or absorption refrigeration cycle for heat recovery from medium and high temperature heat sources such as...
diesel engine exhaust gases.

6. Conclusion

A widespread parametric study is done on the double effect absorption refrigeration/Kalina as well as the first and second configurations of simple absorption refrigeration/Kalina cogeneration cycles. In the parametric study, the effects of changes in the operating parameters are investigated simultaneously. So, it is identified that some parameters have not the same trend in all range of the operating parameter variations and in some parts, the behavior is reverse. The identification of these unusual trends is essential to better designing of cogeneration cycles. Also, the results obtained from the optimization with different objective functions indicated that the high thermodynamic performance of a cycle is not a reason for the favorable economic performance of that cycle. It is observed that although the thermodynamic performance of the first and second configurations of simple absorption refrigeration/Kalina cogeneration cycles is lower than the double effect absorption refrigeration/Kalina cycle, but the economic performance of these cogeneration cycles is far better than the economic performance of the double effect absorption refrigeration/Kalina cycle which is a very interesting result. Also, among the considered cycles, the payback period of the first configuration of simple absorption refrigeration/Kalina cogeneration cycle in all optimum states is less than the corresponding values for the other studied cogeneration cycles.

References


