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Performance Optimization of Three-Heat-Source Irreversible Refrigerators Based Algorithm NSGAII

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Abstract: Throughout present research, an optimization investigation of an irreversible refrigeration absorption system on the basis of a new thermo-ecological criterion. The objective functions which considered are the specific entropy generation rate and the ecological coefficient of performance (*ECOP*). Two objective functions of the ecological coefficient of performance and the specific entropy generation rate are optimized simultaneously using the multi-objective optimization algorithm NSGAII. *ECOP* has been maximized and specific entropy generation rate is minimized in order to get the best performance. Decision making has been done by means of two methods of LINAMP and TOPSIS. Finally, sensitivity analysis and error analysis was performed for the system.

Keywords: Refrigeration system; specific entropy generation rate; ecological coefficient of performance; optimization; NSGAII; Decision making

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1. Introduction

Absorption refrigeration systems working principle is based on the ability of some materials to attract and hold other gases and liquids through exothermic absorption reactions and to vaporize some of the solution through endothermic desorption reactions. The heat can be supplied to the system by thermal energy sources at a temperature of 100 to 200 ℃. Compared with vapor compression systems, absorption refrigeration systems have major advantages: (i) valorizing unutilized sources with moderate temperature by harvesting energy from inexpensive thermal energy ones such as solar energy, geothermal energy and waste heat from cogeneration or process steam plants; (ii) saving the energy in the utilization of primary energy resources; (iii) being less harmful to the environment using environmental-friendly technology; (iv) operating with simple mechanism and (v) providing reliable and quiet cooling owing to its long life and having no moving parts. Application of absorption refrigerators in industrial and domestic sectors is therefore attracting renewed attentions throughout the world [1]. The coefficients of performance (COP) for absorption refrigeration systems are significantly lower when it is compared to the vapor compression refrigeration systems. Numerous publications have studied the optimization of the absorption refrigeration systems to improve its performance. These studies usually chose the coefficient of performance [2-19], the cooling load [4,5,20-22], the thermo-economic criterion [23,24] and the total heat transfer area [6,7] as the objective functions. Aforementioned works performed their analysis usually based on the first law of thermodynamics; however, this method only considers the conversion of energy without taking into account how or where the irreversibilities happen in a system or during a process. In the real absorption refrigeration systems irreversibilities occur which impose considerable amount of energy consumption for high cooling load. The irreversible and spontaneous process in a system is considered as “noble” into heat energy conversion. Chen et al. [3] and Yan and Lin [8] achieved the best agreement between cooling and dissipation rates of an absorption refrigerator using criterion based on the thermo-ecological optimization. The ecological objective function is illustrated as the difference between the rates of the availability loss and cooling load. The ecological optimization method comprises both the first and second laws of thermodynamics. However, the main drawback for thermo-ecological criterion procedure is due to the negative values the objective function may take [25,26]. Therefore, a new thermo-ecological objective function called ecological coefficient of performance (ECOP) was recently developed [25,27] to remove this limitation. By its definition, the cooling load per unit loss rate of availability, the resulting values are always positive and dimensionless. Ust et al. [28] was the first team that performed an optimization analysis for the heat engines using new thermo-ecological objective function. In the present study, this optimization analysis is extended to an irreversible refrigerator with three heat sources and parametric sensitivity is evaluated for investigation of the effects on the global and optimal performances.

Solving multi-objective optimization problems is too difficult because the resulting different objective functions should be satisfied simultaneously while they may even conflict. Evolutionary algorithms (EA) were the first techniques developed and utilized during the mid-eighties which enabled solving problems of such generic class stochastically [29]. When such a method is to be used, a multi-objective issue gives rise to an assortment of optimal results, each of the objective functions is satisfied at an acceptable level where the other solutions are not being dominated [30]. In general, multi-objective optimization show a countless assortment of possible results called Pareto frontier, whose assessed vectors in the objective function space characterize the finest probable trade-offs. Nowadays, multi-objective optimization of various systems in energy and thermodynamics engineering is generating interest in many researchers throughout the world [31-46].

Paper presented here employs the evolutionary algorithm with ECOP and rate of specific entropy generation as the optimization objectives to study the performance optimization of the irreversible refrigerators with three heat source. The decision variables include the refrigerator thermal operating parameters which are the generator working fluid temperature (T_1), the evaporator working fluid temperature (T_2) and the working fluid temperatures in the condenser and absorber (T_3).

2. Thermodynamics analysis of an irreversible three-heat-source refrigerator system

An absorption refrigeration system comprises of four main components: a condenser, a generator, an absorber, and an evaporator [2-4, 47-53]. Fig. 1 illustrates the schematics for an absorption refrigeration system. In this study, $\dot{Q}_E$ denotes the heat input rate from the cooling space at temperature T_E to the evaporator, $\dot{Q}_G$ denotes the rate of transferred heat from the heat source at temperature T_G to the generator, $\dot{Q}_C$ denotes the rate of transferred heat from the condenser to the heat sink at temperature T_C and $\dot{Q}_A$ denotes the rate of rejected heat from the absorber to the heat sink at temperature T_A. The energy input to the generator is much more than the energy input required to pump the rich solution to the generator and often assumed to be negligible in the thermodynamic analysis [2,3,50,53].

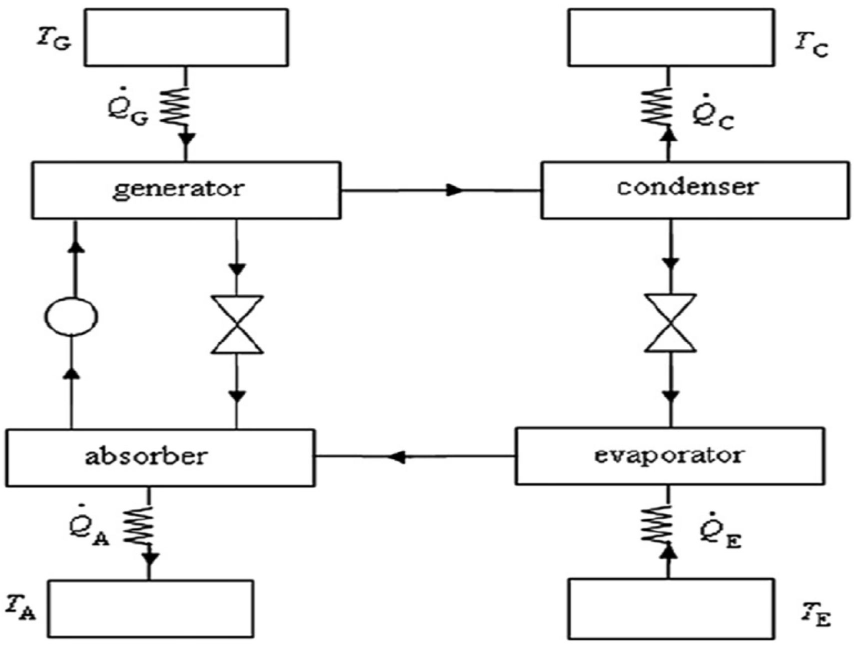


Figure. 1. Schematic diagram of an absorption refrigerator

The energy balance for the system (first law of thermodynamics) can be expressed as:

$$\dot{Q}_G + \dot{Q}_E - \dot{Q}_C - \dot{Q}_A = 0 \tag{1}$$

For the equal absorber and condenser temperatures, the absorption refrigeration cycle works between three temperature stages. The irreversible factors strongly influence the performance of an absorption refrigeration system [2] which imposes making many considerations when the performance of such system is analyzed [50]: the working fluid cycle comprises of three adiabatic and three isothermal processes which are all irreversible. There are finite temperature differences between the external heat sink and heat source temperatures with the working fluid temperatures in the three isothermal processes with the intention of the heat is conveyed irreversibly under these temperature difference as it is depicted throughout Fig. 2. In this figure, $\dot{Q}_O = \dot{Q}_C + \dot{Q}_A$, and the working fluid temperatures in the generator, evaporator and condenser are denoted by T_1, T_2 and T_3, respectively. Assuming that the working fluid has the same temperature in the condenser and the absorber, T_3 is also the temperature of the working fluid in the absorber [50,52,53]. $\dot{Q}_L$ stands for the heat transferred from the heat sink to the cooling space.

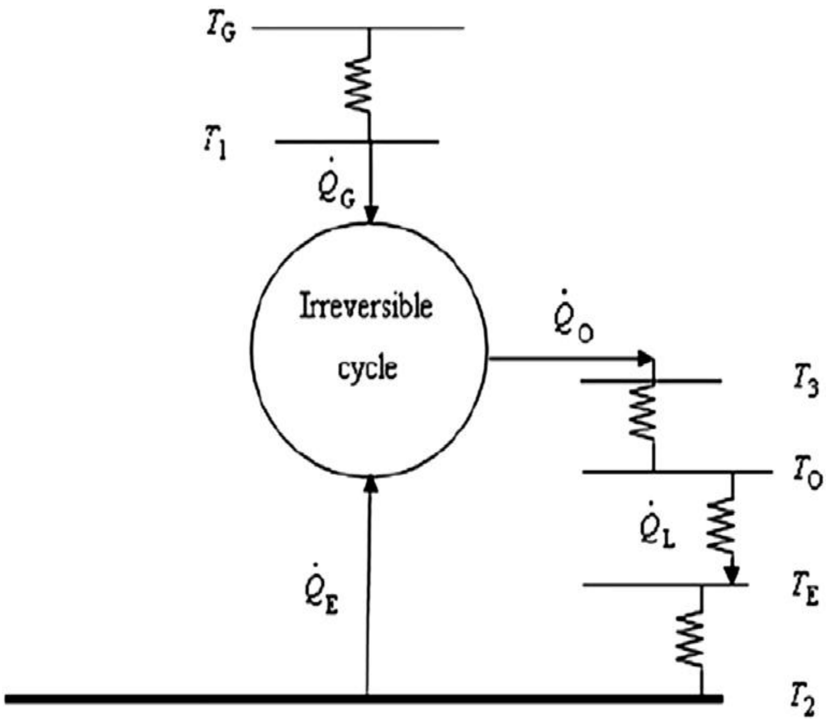


Figure. 2. Irreversible cycle model of an absorption refrigerator

The working fluid and the heat reservoirs linearly exchanges heat between each other, so that the heat transfer equation can be expressed as [2,50-53]:

$$\dot{Q}_G = U_G A_G (T_G - T_1) \tag{2}$$

$$\dot{Q}_E = U_E A_E (T_E - T_2) \tag{3}$$

$$\dot{Q}_O = U_O A_O (T_3 - T_O) \tag{4}$$

In Equations (2)-(4), U_G and U_E are the overall coefficients of heat transfer in the generator and evaporator, correspondingly. The area of heat transfer throughout the evaporator, generator, absorber and condenser are denoted by A_E, A_G, A_A and A_C, correspondingly and U_O is the overall heat transfer coefficient in the absorber and condenser assuming they have the identical overall heat transfer coefficients [2,50].

The absorption refrigeration cycle exchange heat only with the three heat sources at temperatures T_G, T_E and T_O, hence the total heat transfer area A between the external heat reservoirs and the system cycle can be written as [50,53]:

$$A = A_G + A_E + A_O \tag{5}$$

$$A_O = A_A + A_C \tag{5a}$$

The heat leakage rate $\dot{Q}_L$ at temperature T_O from the heat sink to the cold reservoir at temperature T_E with K_L as the heat leakage coefficient is expressed as [50,53]:

$$\dot{Q}_L = K_L(T_o - T_E) \tag{6}$$

An absorption refrigeration system is a combination of two assemblies: a generator-absorber assembly as a heat engine and an evaporator-condenser assembly as a refrigerator [47, 48]. Therefore, the effect of the internal dissipations of the working fluid on the performance of the system can be studied by introducing two parameters for internal irreversibilities including the generator-absorber assembly and the evaporator-condenser assembly internal irreversibilities [53]:

$$I_1 = \frac{\frac{\dot{Q}_A}{T_3}}{\frac{\dot{Q}_G}{T_1}} \quad ,(I_1 \geq 1) \tag{7}$$

$$I_2 = \frac{\frac{\dot{Q}_C}{T_3}}{\frac{\dot{Q}_E}{T_2}} \quad ,(I_2 \geq 1) \tag{8}$$

where the two irreversibilities factors I_1 for generator-absorber assembly and I_2 for evaporator-condenser assembly is presented based on the second law of thermodynamics.

If the working fluid cycles in both the evaporator-condenser assembly and the generator-absorber assembly are reversible, $I_1 = I_2 = 1$ and when the cycles of the working fluid in these assemblies are irreversible, $I_1 > 1$ and $I_2 > 1$.

The coefficient of performance, the specific cooling load, and the rate of specific entropy generation for a three-heat-source absorption refrigerator can be obtained using equations (1), (2) and (8), as they are given by equations (9), (10) and (12), respectively:

$$COP = \frac{\dot{Q}_E - \dot{Q}_L}{\dot{Q}_G} = \frac{T_2(T_1 - I_1T_3)}{T_1(I_2T_3 - T_2)} \times \{1 - \xi(T_O - T_E)\left[\frac{1}{U_E(T_E - T_2)} + \frac{T_1(I_2T_3 - T_2)}{U_G(T_G - T_1)(T_1 - I_1T_3)T_2} + \frac{I_1T_3(I_2T_3 - T_2)}{U_O(T_3 - T_O)(T_1 - I_1T_3)T_2} + \frac{I_2T_3}{U_OT_2(T_3 - T_O)}\right]\} \tag{9}$$

$$R = \frac{\dot{Q}_E - \dot{Q}_L}{A} = \left[\frac{1}{U_E(T_E - T_2)} + \frac{T_1(I_2T_3 - T_2)}{U_G(T_G - T_1)(T_1 - I_1T_3)T_2} + \frac{I_1T_3(I_2T_3 - T_2)}{U_O(T_3 - T_O)(T_1 - I_1T_3)T_2} + \frac{I_2T_3}{U_OT_2(T_3 - T_O)}\right]^{-1} - \xi(T_O - T_E) \tag{10}$$

$$S = \frac{\dot{\sigma}}{A} = \frac{\frac{\dot{Q}_O - \dot{Q}_L}{T_O} - \frac{\dot{Q}_G}{T_G} - \frac{\dot{Q}_E - \dot{Q}_L}{T_E}}{A} \tag{11}$$

$$S = (\frac{1}{T_E} - \frac{1}{T_O}) \times \{\xi(T_O - T_E) - \left[1 - \frac{\varepsilon_r T_1(IT_3 - T_2)}{T_2(T_1 - IT_3}\right]\left[\frac{1}{U_E(T_E - T_2)} + \frac{T_1(I_2T_3 - T_2)}{U_G(T_G - T_1)(T_1 - I_1T_3)T_2} + \frac{I_1T_3(I_2T_3 - T_2)}{U_O(T_3 - T_O)(T_1 - I_1T_3)T_2} + \frac{I_2T_3}{U_OT_2(T_3 - T_O)}\right]^{-1}\} \tag{12}$$

In equations (9)-(12), $\varepsilon_r = (1-\frac{T_O}{T_G})(\frac{T_E}{T_O - T_E})$ is the coefficient of performance for a reversible three-hea.t-source refrigerator and $\xi = \frac{K_L}{A}$ stands for the heat leakage coefficient. For an absorption refrigerator system with three heat sources and two internal irreversibility factors, the innovative thermo-ecological objective function named ecological coefficient of performance (*ECOP*) is given in equation (13) based on the description for the general thermo-ecological benchmark function [25,27,50,53]:

$$ECOP = \frac{R}{T_{env} S} \tag{13}$$

3. Multi-objective optimization with evolutionary algorithms

3.1. Optimization via EA

A computer simulation program is used for the optimization problem to obtain the Pareto frontier executing the genetic algorithm (GA). Genetic algorithm which is characterized under the evolutionary algorithms was first proposed and developed by John Holland in the 1960s is the integration of numerical methods in optimization and the natural adaptation approach using computer algorithms [29,30]. The simulation program is developed to generate acceptable solutions through evolution of the population of abstract representations (chromosomes) of the candidate solutions (individuals). The evolution starts with the random generation of individuals and the generation process is iterated. Every individual fitness is evaluated in every step so that multiple individuals can be selected randomly from the population according to their fitness. Finally, a new population is generated by their modification through recombination and possible random mutation. The generated population in each step is required in the next step of the algorithm. When the number of generations reaches its maximum, or if the population reaches its satisfactory fitness level, the algorithm terminates however, the latter do not lead to an acceptable solution. Using this method is very effective especially in solving nonlinear problems [29, 30]. Furthermore, significant strides have been made to reduce the complexity of classical methods using various tests on complex engineering and mathematical problems [29, 30]. This study uses the multi-objective evolutionary algorithms (MOEAs) as a recently developed method as its schematics is illustrated in Fig. 3 [32-37,44-46]. Instead of considering binary codes, they are replaced by the real values of decision variables.

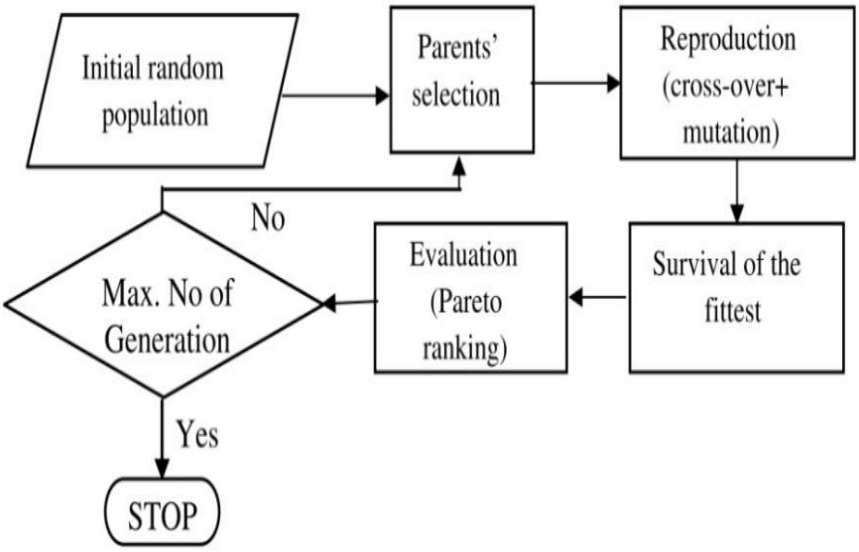


Figure.3. Scheme for the multi-objective evolutionary algorithm used in the present study

3.2. Objective functions, constraints and decision variables

Two strategic objective functions for optimization comprise the specific entropy generation rate (should be minimalized), the ecological coefficient of performance (should be maximized) denoted by Eqs.(12) and Eqs.(13), respectively.

In the present research, three decision parameters are involved as following as:

T_1: The temperatures of the working fluid in the generator

T_2 : The temperatures of the working fluid in the evaporator

T_3: The temperatures of the working fluid in the condenser and absorber

The objective functions with regard to below limitations are resolved:

$$395 \leq T_1 \leq 402 \tag{14}$$

$$262 \leq T_2 \leq 272 \tag{15}$$

$$304 \le T_3 \le 314 \tag{16}$$

3.3. Decision-making in the multi-objective optimization

After optimization progression with multi variables and objectives, selecting an ultimate optimum outcome from the results gained by evolutionary approach has a great importance. Thanks to this fact, numerous methods that known as decision making techniques can be execute to determine desire optimal variables from the frontier of Pareto that is previously gained. Throughout this research, two robust, high performance and well-known decision maker techniques including LINMAP and TOPSIS approaches are utilized. Ultimate optimum outcomes were determined on the basis of the expert knowledge and indexes through results that proposed with the aim of decision maker approaches. Extensive description of two decision makers can be found in following references [32-37,44-46].

4. Result an discussion

The ecological coefficient of performance (*ECOP*) is maximized simultaneously and the specific entropy generation rate (S) is minimalized at the same time via the multi-objective optimizing scheme which performs on the basis of the NSGA-II method.

By the way, optimization is accomplished with objective functions that are illustrated by Eqs. (12) and (13) limitations which are formulated with Eqs. (14)-(16).

With the intention of have uniformity with preceding publications, qualifications of the Irreversible refrigerator cycle are comprised as following as [50, 53]

$$T_G = 403K\ ,\ T_O = 303K\ ,\ T_{env} = 290K\ ,\ T_E = 273K\ ,\ U_G = 1163\,(W\,m^{-2}\,K^{-1})\ ,$$

$$U_E = 2326\,(W\,m^{-2}\,K^{-1})\ ,\ U_O = 4650\,(W\,m^{-2}\,K^{-1})\ ,\ \xi = 2\ ,\ I_1 = 1\ ,\ I_2 = 1\,.$$

Pareto optimal frontier exhibited in Fig.4 Also, obtained optimal solutions of LINMAP and TOPSIS methods exhibited in Fig.4. As clear be seen from Fig.4, optimal solution of $ECOP$ varied of 55.43 to 57.6 and optimal solution of S varied of 0.049 to 0.57.

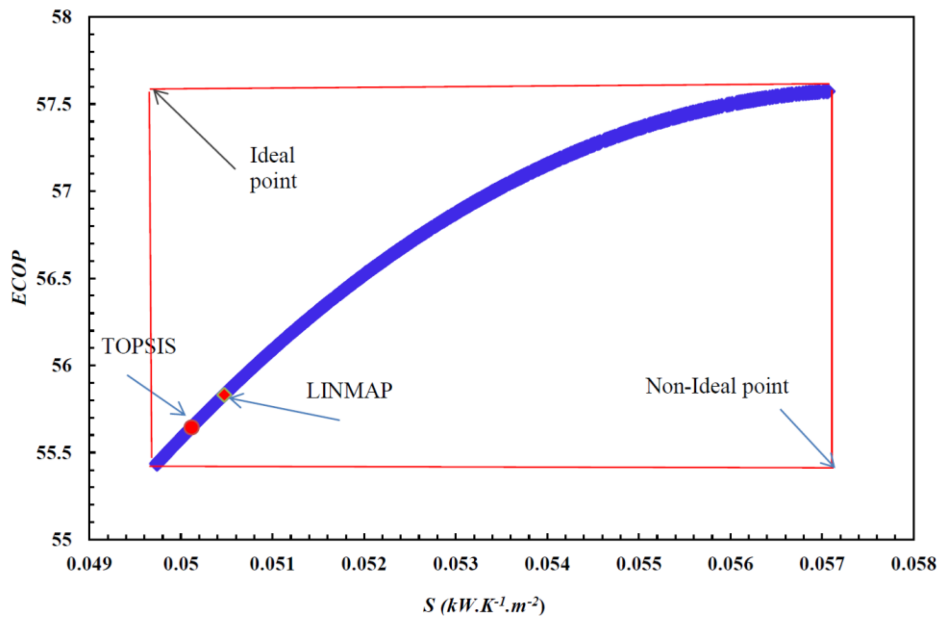


Figure.4. Pareto frontier (Pareto optimal solutions) for *S* versus *ECOP* using NSGA-II

Figs 5 to 7 are exhibited the scattering of different values of decision parameters within their permissible rang for the optimum design points on the Pareto front. It can be seen from Fig.5 that distribution of T_1 in $T_1 \approx 402$ was marked by blue line and T_1 obtained higher value. From Fig.6 it can be seen that distribution of T_2 in $T_2 = 272$ was marked by blue line and T_2 obtained higher value. It can be seen from Fig.7 that distribution of T_3 in $T_3 = 304K$ was marked by blue line and T_3 obtained lower value.

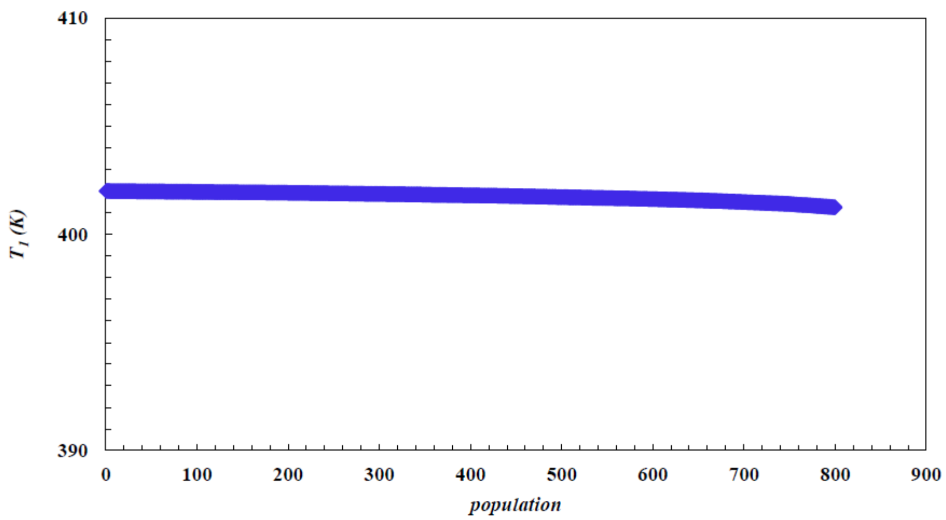


Figure.5. The distribution of T_1 for the optimal points on Pareto front.

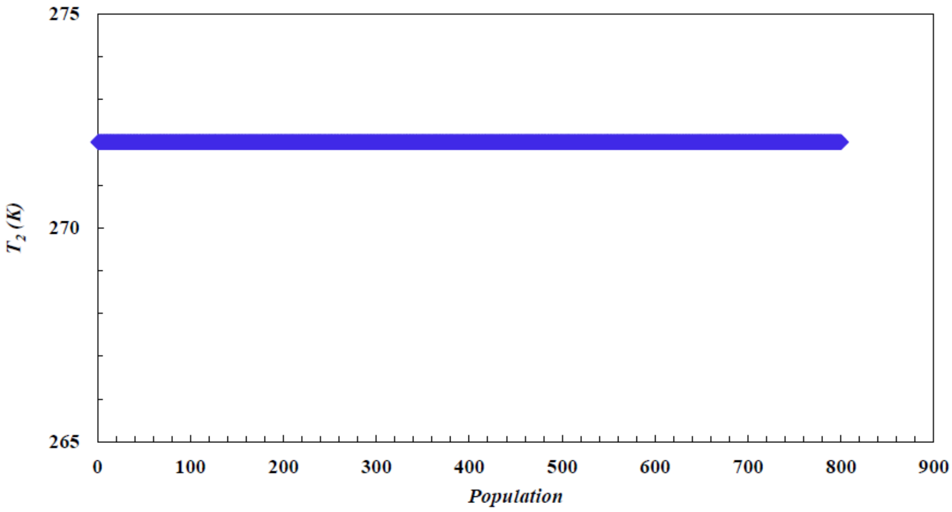


Figure.6. The distribution of T_2 for the optimal points on Pareto front.

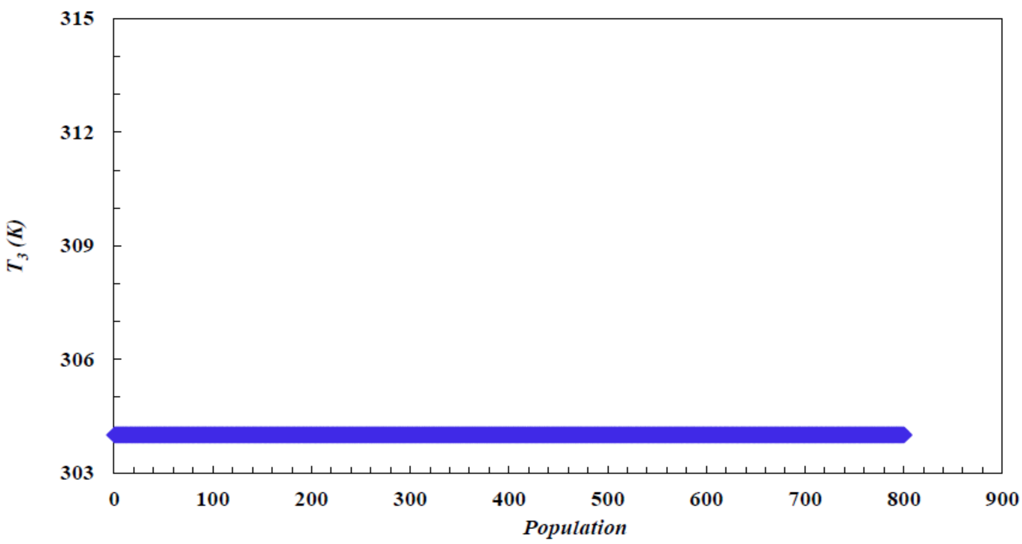


Figure.7. The distribution of T_3 for the optimal points on Pareto front.

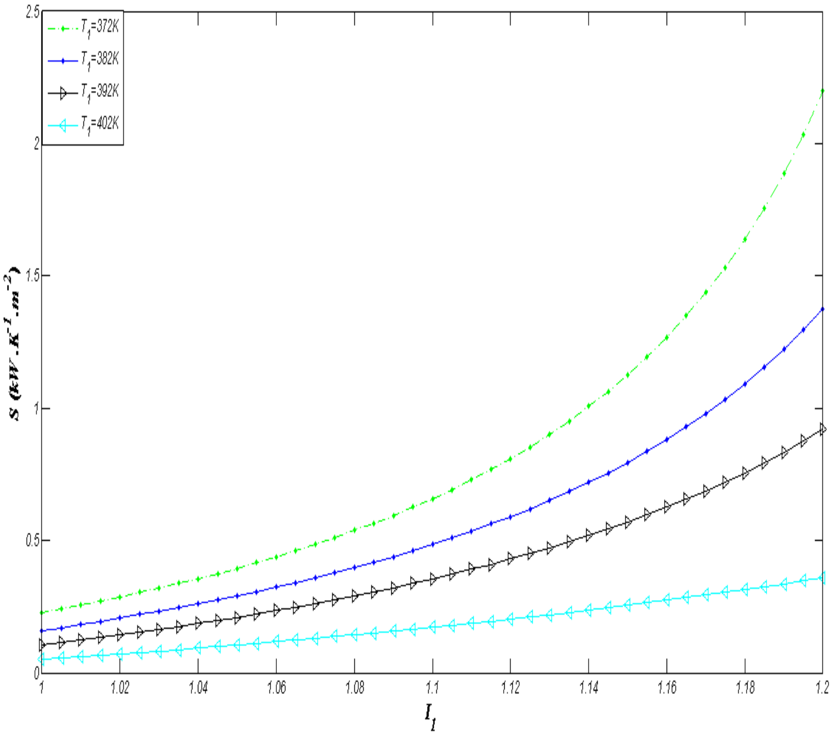
The optimum outcomes for decision variables and objective functions executing LINMAP and TOPSIS decision-makers are explained in Table 1.

Table 1: Decision making of multi-objective optimal solutions

Decision Making Method	Decision variables			Objective functions	
	T_1	T_2	T_3	S	$ECOP$
TOPSIS	401.96	*272*	*304*	0.0501	55.64
LINMAP	401.94	*272*	*304*	0.0504	55.83
Ideal Point	-	-	-	0.0497	57.57
Non-ideal Point	-	-	-	0.0570	55.43

*4.1. Sensitivity analysis***:**

From Fig. 8 it can be seen that, the specific entropy generation rate increased considerably with increasing the parameter of internal irreversibility for absorber-generator assembly (I_1) at various values of the working fluid temperatures throughout the generator (T_1) and the ecological coefficient of performance decrease considerably with increasing parameter of internal irreversibility for absorber-generator assembly (I_1) at various values of the working fluid temperatures throughout the generator (T_1).



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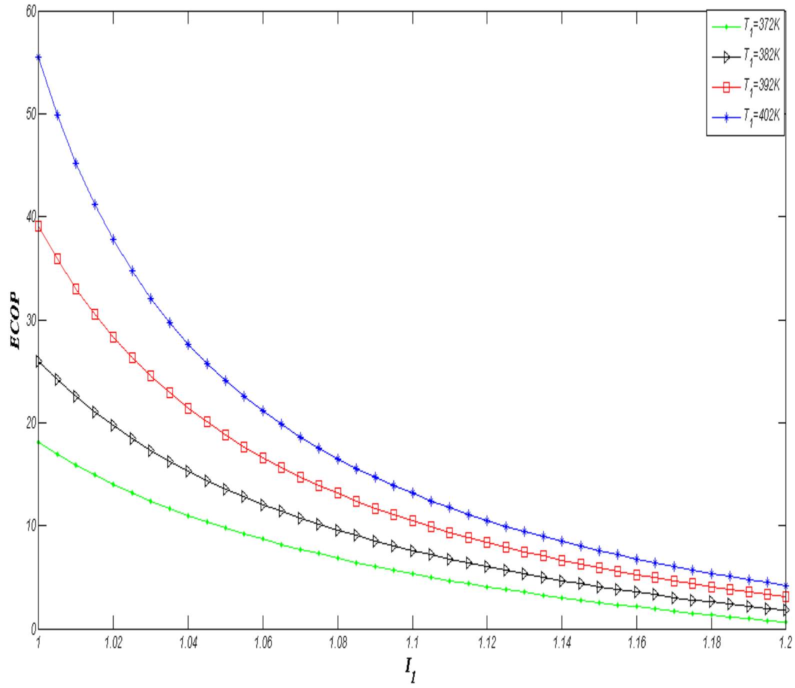

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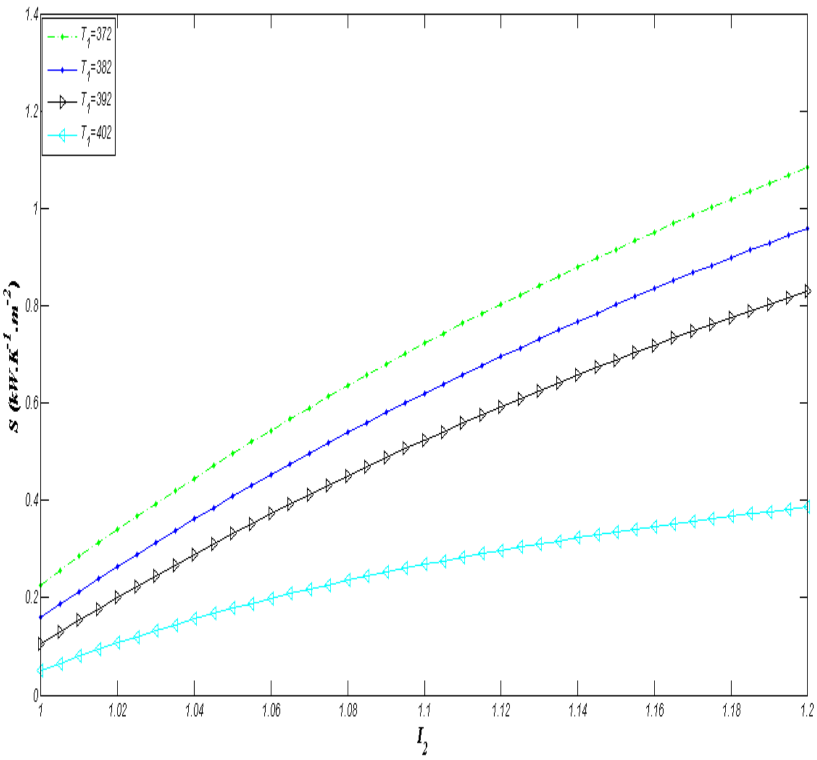
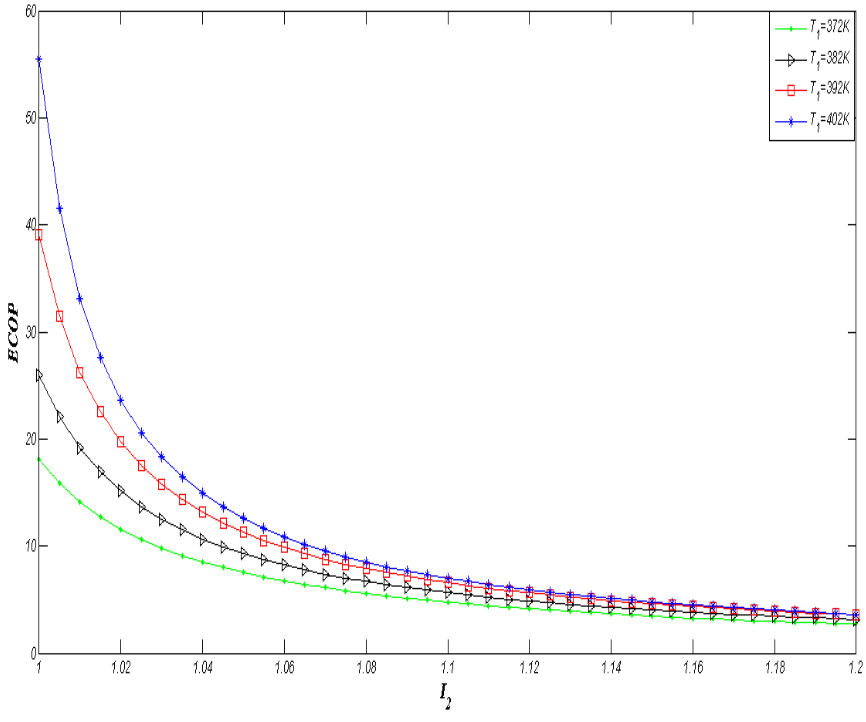
Fig.8. Effects of the internal irreversibility parameter for generator-absorber assembly (I_1) and the temperatures of the working fluid in the generator (T_1) on the (a) specific entropy generation rate, (b) Ecological Coefficient of performance

From Fig. 9 it can be seen that, the specific entropy generation rate increased significantly with increasing the parameter of internal irreversibility for condenser-evaporator assembly (I_2) at various values of the working fluid temperatures throughout the generator (T_1) and the ecological coefficient of performance decrease noticeably with increasing the parameter of internal irreversibility for condenser-evaporator assembly (I_2) at various values of the working fluid temperatures throughout the generator (T_1).



T_1=372
T_1=382
T_1=392
T_1=402
S (kW.K-1.m-2)
I_2

a

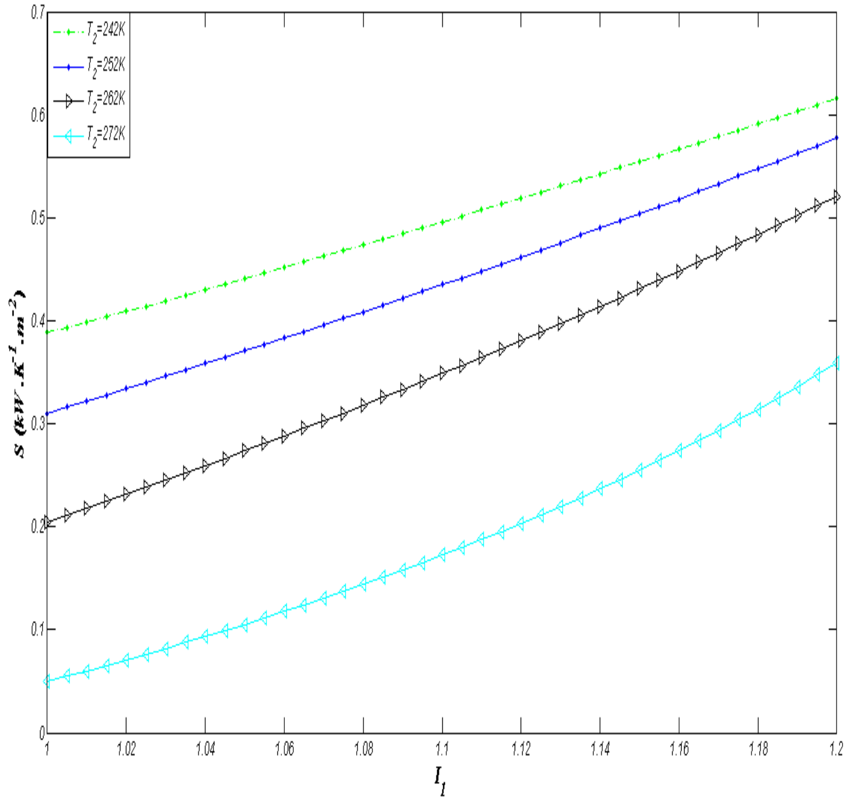


T_1=372K
T_1=382K
T_1=392K
T_1=402K
ECOP
I_2

b

Fig.9. Effects of the internal irreversibility parameter for evaporator-condenser assembly (I_2) and the temperatures of the working fluid in the generator (T_1) on the (a) specific entropy generation rate, (b) Ecological Coefficient of performance

In the Fig. 10 different system objective functions against the parameter of internal irreversibility for absorber-generator assembly (I_1) in the working fluid temperatures within the evaporator (T_2) are plotted. And in these figures by increasing the parameter of internal irreversibility for absorber-generator assembly (I_1), the specific entropy generation rate will be raised and the ecological coefficient of performance will be down.



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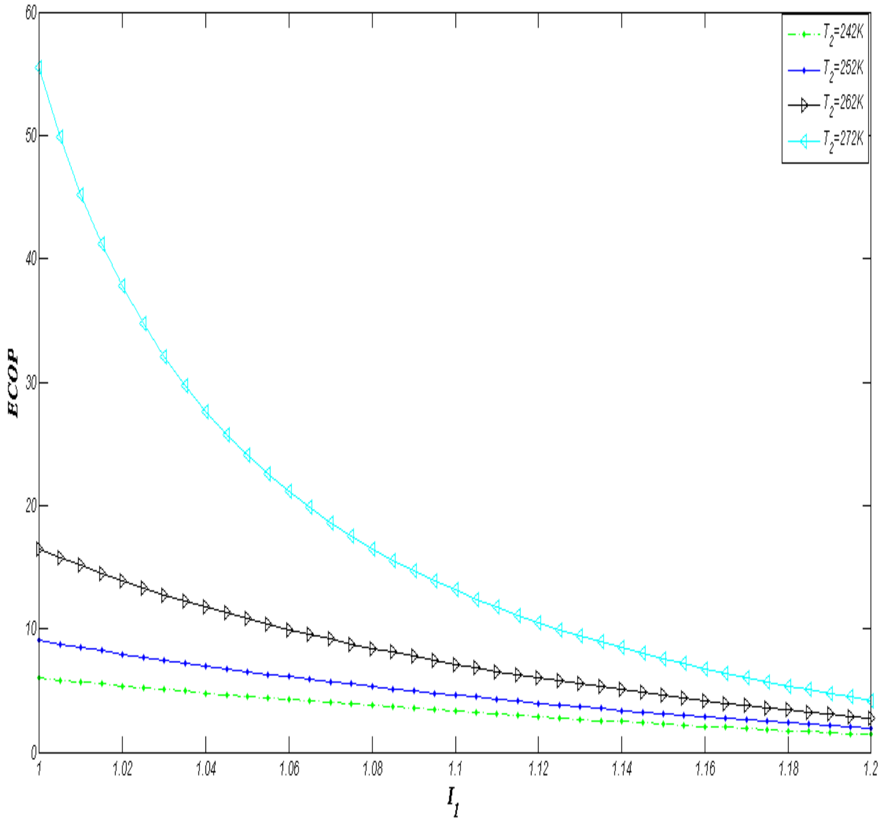

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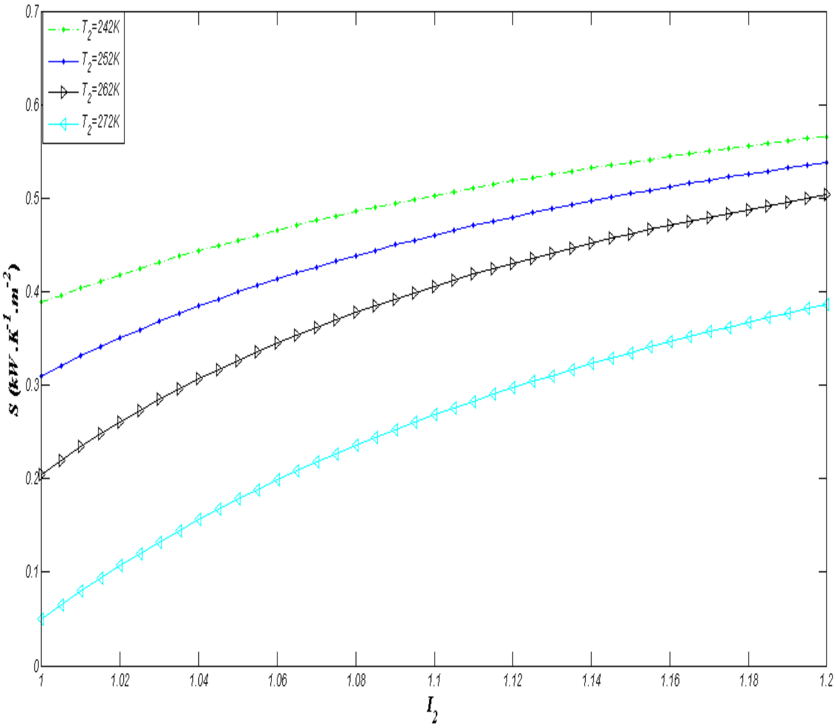
Fig.10. Effects of the internal irreversibility parameter for generator-absorber assembly (I_1) and the temperatures of the working fluid in the evaporator (T_2) on the (a) specific entropy generation rate, (b) Ecological Coefficient of performance

In the Fig. 11 different system objective functions against the parameter of internal irreversibility for condenser-evaporator assembly (I_2) in the working fluid temperatures within the evaporator (T_2) are plotted. And in these figures by increasing the parameter of internal irreversibility for condenser-evaporator assembly (I_2), the specific entropy generation rate will be raised and the ecological Coefficient of performance will be down.



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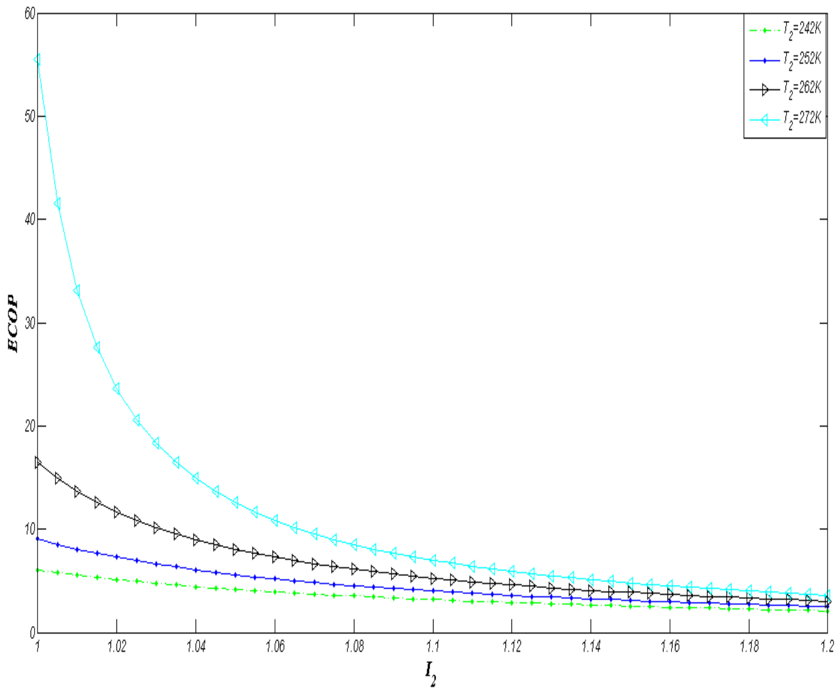

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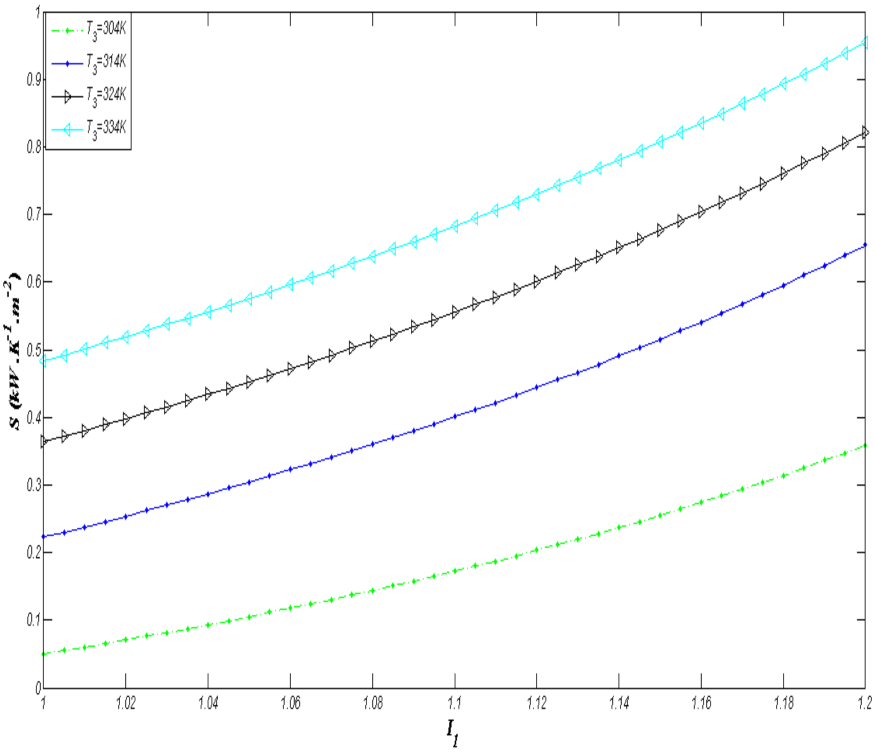
Fig.11. Effects of the internal irreversibility parameter for evaporator-condenser assembly (I_2) and the temperatures of the working fluid in the evaporator (T_2) on the (a) specific entropy generation rate, (b) Ecological Coefficient of performance

From Fig. 12 it can be seen that, the specific entropy generation rate increase considerably with increasing of the parameter of internal irreversibility for absorber-generator assembly (I_1) at various values of the working fluid temperatures throughout the absorber and condenser (T_3) and the ecological coefficient of performance decrease considerably with increasing of the parameter of internal irreversibility for absorber-generator assembly (I_1) at various values of the working fluid temperatures throughout the absorber and condenser (T_3).



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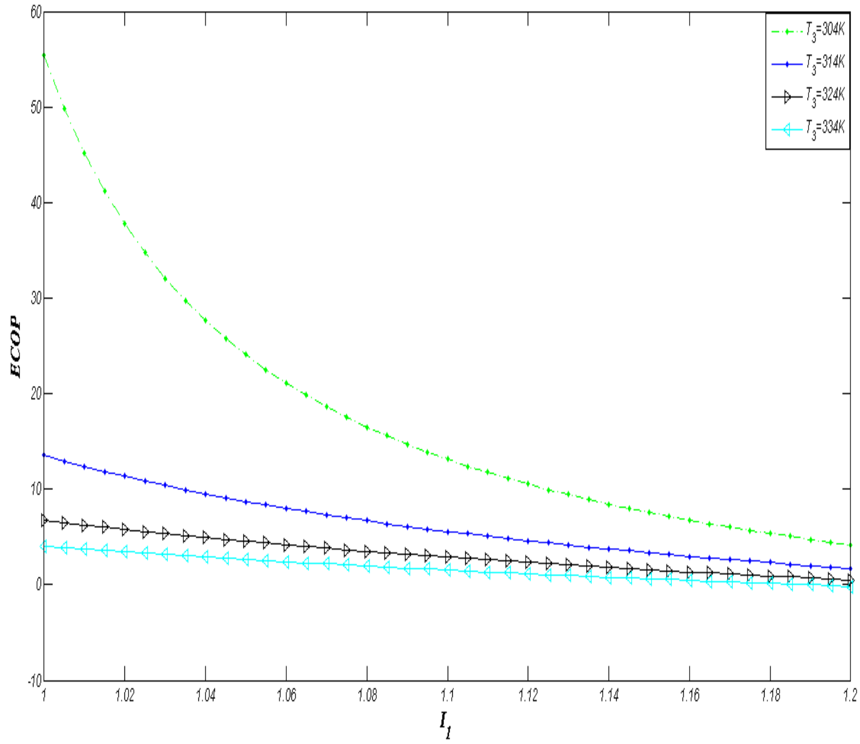

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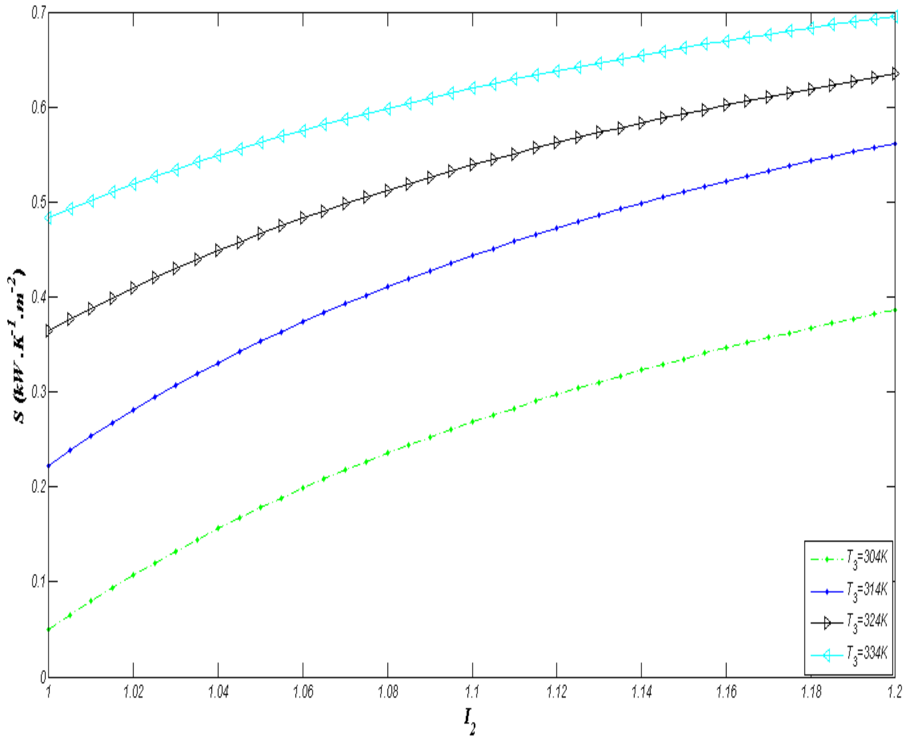
Fig.12. Effects of the internal irreversibility parameter for generator-absorber assembly (I_1) and the temperatures of the working fluid in the condenser and absorber (T_3) on the (a) specific entropy generation rate, (b) Ecological Coefficient of performance

In the Fig. 13 different system objective functions against the parameter of internal irreversibility for condenser-evaporator assembly (I_2) in the working fluid temperatures in the absorber and condenser (T_3) are plotted. And in these figures by increasing the parameter of internal irreversibility for condenser-evaporator assembly (I_2), the specific entropy generation rate will be raised and the ecological coefficient of performance will be down.



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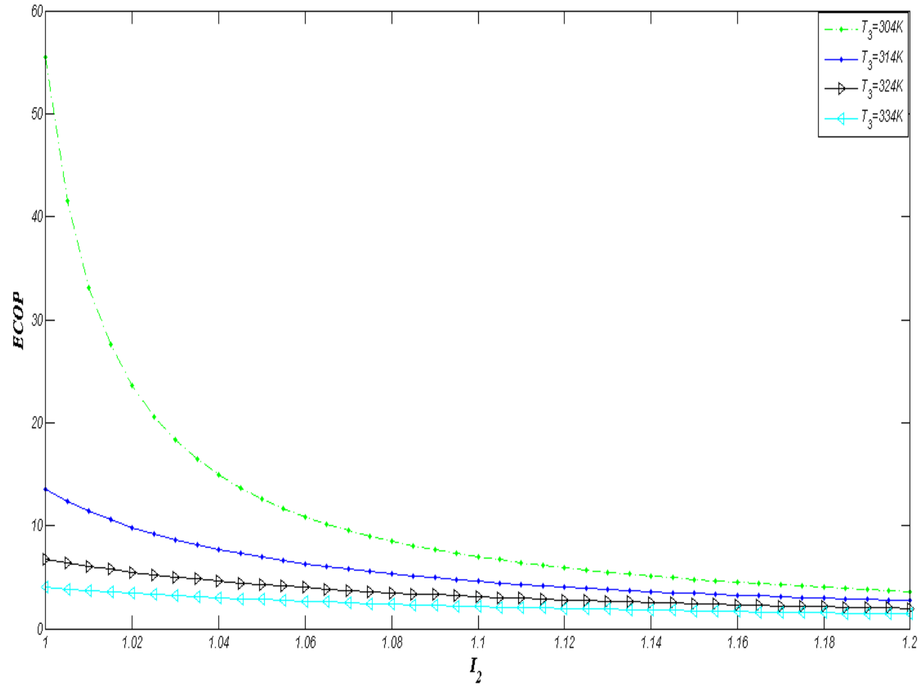

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Fig.13. Effects of the internal irreversibility parameter for evaporator-condenser assembly (I_1) and the temperatures of the working fluid in the condenser and absorber (T_3) on the (a) specific entropy generation rate, (b) Ecological Coefficient of performance

4.2. Error Analysis:

Error analysis of used techniques is accomplished through mean absolute percentage error (MAPE). To assess this goal, 30 runs of each technique is executed to acquire closing result via TOPSIS and LINMAP decision makers. First row of Table 2 demonstrates maximum absolute percentage error (MAAE) of two decision makers. Moreover, second row of Table 2 reports MAPE and MAAE of the mentioned methods.

Table 2: Error analysis based on the mean absolute percent error (MAPE) method.

Decision Making Method	**TOPSIS**		**LINMAP**	
Objectives	*ECOP*	*S*	*ECOP*	*S*
Max Error %	0.066	0.118	0.044	0.129
Average Error %	0.055	0.094	0.025	0.072

5. Conclusions

In this study, thermodynamic analysis has been applied to determine the specific entropy generation rate (S) and the ecological coefficient of performance ($ECOP$) of the refrigerator. The specific entropy generation rate (S) and the ecological coefficient of performance ($ECOP$) of the refrigerator are included concurrently for multi-objective optimization the temperatures of the working fluid in the generator (T_1), the temperatures of the working fluid in the evaporator (T_2) and the temperatures of the working fluid in the condenser and absorber

(T_3) are counted as design variables. Multi objective evolutionary algorithm is accomplished on the basis of the NSGA-II method and the Pareto optimum frontier within objectives space is gained. A closing optimum result is elected from outcomes of the Pareto frontier executing two decision makers including LINMAP and TOPSIS techniques.

Nomenclature

A	total heat-transfer area (m^2)
COP	coefficient of performance
$ECOP$	ecological coefficient of performance
I_1	internal irreversibility parameter for generator-absorber assembly
I_2	internal irreversibility parameter for evaporator-condenser assembly
K_L	the heat leakage coefficient (kW K^{-1})
R	specific cooling load (kW m^{-2})
S	specific entropy generation rate (kW K^{-1} m^{-2})
T	temperature (K)

Symbol

$\dot{\sigma}$	entropy generation rate (kW K^{-1})
ξ	heat leakage coefficient (kW K^{-1} m^{-2})
ε_r	coefficient of performance for reversible three heat-source refrigerator

Subscript

s

1	working fluid in generator
2	working fluid in evaporator
3	working fluid in absorber and condenser
A	absorber
C	condenser
E	evaporator
G	generator

env environment conditions

O absorber and condenser

Conflicts of Interest

The authors declare no conflict of interest.

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