Thermodynamic analysis and evolutionary algorithm based on multi-objective optimization of performance for irreversible four-temperature-level refrigeration

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Abstract – This paper presents a developed ecological function for absorption refrigerators with four-temperature-level. Moreover, aforementioned absorption refrigerator is optimized by implementing ecological function. With the aim of the first and second laws of thermodynamics, an equivalent system is initially determined. To reach the addressed goal of this research, two objective functions: the coefficient of performance (*COP*) and the ecological function (*E*) have been involved in optimization process simultaneously. The first aforementioned objective function has to maximize the rest objective functions, on the other hand, have to maximize in parallel optimization process. Developed multi objective evolutionary approaches (MOEAs) on the basis of NSGA-II method are implemented throughout this work.

Key words: Coefficient of performance / NSGA-II method / thermodynamic / absorption refrigerator / optimization

1 Introduction

Absorption refrigerators can provide cooling with many different sources such as renewable energies or waste heat. Besides their various sources, low costs and low emission are some factors that make them very popular. It has been shown that combination of this system with heat and power sources (CHP) could be highly beneficial in terms of economic aspects. Finite-time thermodynamics has been used since 1970s and Angulo-Brown has suggested an ecological criterion for optimization process of refrigerating systems. $\dot{E} = \dot{W} - T_L \dot{\sigma}$ is used for finite-time Carnot machines. T_L is the temperature of cold reservoir and σ is entropy generation. Yan suggested that $\dot{E} = \dot{W} - T_0 \dot{\sigma}$ is more reliable. T_0 is the ambient temperature. We can see a great interest in previous works for optimizing the refrigeration cycle. Bhardway et al. [1, 2] optimized the refrigeration cycle using finite time thermodynamics. Huang and colleagues used *COP*, surface area,

and ecological criteria for irreversible engine with four temperature levels [3]. Chen developed models for absorption refrigerators [4, 5]. Sun et al. [6] optimized the relation between entropy generation in heating heat exchanger and heating load. Also Chen and colleagues presented an analysis of absorption refrigerator cycle with four temperature levels [7]. Chen and Yan optimized the irreversible absorption heat transformers based on ecological criterion [8].

Also some authors performed an optimization based on ecological criterion and irreversible Carnot engines with three temperature levels [9, 10]. Fathi and colleagues did a research solar absorption cooling [11]. Also, there are many optimization processes for absorption refrigerators in references [12–15]. Besides, some optimization processes such as “advanced exergy based analysis approaches” and “exergy-entropy relationship” can be found in literature [16–18]. Hellmann investigated the effects of complementary limitation, or additional operational variable [19]. We also evolved sensitivity analysis of refrigerators with four heat reservoirs [20, 21]. These are done by optimization of coefficient of performance for an

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irreversible machine with four finite reservoirs (refrigerator and heat pump), with parametric analysis. Multi-objective optimization is useful way for solving engineering problems at various fields for research [22–24].

A multi objective optimization requires simultaneous satisfaction of various objective functions. Evolutionary algorithm or EA was introduced in 20th century for solving multi objective optimization problems [25]. In a multi objective optimization a set of routes is gained, each of them satisfies the objectives at a satisfactory degree independent of another route [26]. A countless group of routes is being generated called Pareto, whose vectors show the best feasible solutions through the objectives region. Different fields of science have used multi objective optimization as a powerful tool for optimization [27–34].

In our study, in order to maximize the coefficient of performance (COP) and the ecological function (E), multi-objective optimization algorithms have been employed. Error analysis was performed to determine accuracy of ultimate results of various decision making methods.

2 Thermodynamic analysis of system

A thermodynamic analysis has been done for proposed system, based on equations presented in [35–40]. The ambient temperature is fixed at 290 K. Figure 1 shows the schematic absorption refrigerator studied in this work.

2.1 Thermodynamic analysis of the generator-absorber assembly (heat engine part)

Thanks to the first law of thermodynamics,

$$\dot{Q}_G - \dot{Q}_A - \dot{W} = 0 \quad (1)$$

In which, $\dot{Q}_A$ (heat output to the absorber heat sink) and $\dot{Q}_G$ (heat input from the generator heat source) can be formulated as following:

$$\dot{Q}_G = \alpha A_G (T_G - T_g) \quad (2)$$

$$\dot{Q}_A = \beta A_A (T_a - T_A) \quad (3)$$

Thanks to the second law of thermodynamics [35–40],

$$\begin{aligned} \frac{\dot{Q}_G}{T_g} - \frac{\dot{Q}_A}{T_a} &\leq 0 \\ \frac{\dot{Q}_A}{T_a} &= I_H \frac{\dot{Q}_G}{T_g} \end{aligned} \quad (4)$$

In which, I_H represents the parameter of internal irreversibility for generator-absorber assembly. $I_H = 1$ should be considered for the reversible cycles, and $I_H > 1$ for the irreversible cycles. Working fluid temperature ratio (x_H),

heat transfer surface area ratio (a_H), and total heat transfer surface area ($A_{T,H}$) for the absorber-generator assembly can be defined as following:

$$x_H = \frac{T_a}{T_g} \quad (5)$$

$$a_H = \frac{A_A}{A_G} \quad (6)$$

$$A_{T,H} = A_G + A_A \quad (7)$$

T_g , T_a , and $\dot{Q}_G$ can be formulated by employing Equations (2), (3) to (4)–(7) as following:

$$T_g = \frac{I_H \alpha T_G x_H + a_H \beta T_A}{x_H (a_H \beta + I_H \alpha)} \quad (8)$$

$$T_a = \frac{I_H \alpha T_G x_H + a_H \beta T_A}{(a_H \beta + I_H \alpha)} \quad (9)$$

$$\dot{Q}_G = \frac{\alpha A_{T,H}}{1 + a_H} \left(\frac{a_H \beta (T_G x_H - T_A)}{x_H (a_H \beta + I_H \alpha)} \right) \quad (10)$$

2.2 Thermodynamic analysis of the evaporator-condenser assembly (refrigerator part)

Based on the concept of the first law of thermodynamics,

$$\dot{Q}_C - \dot{Q}_E - \dot{W} = 0 \quad (11)$$

Here, $\dot{Q}_E$ (heat input to the evaporator) and $\dot{Q}_C$ (heat rejection from the condenser) are

$$\dot{Q}_C = \mu A_C (T_c - T_C) \quad (12)$$

$$\dot{Q}_E = \theta A_E (T_E - T_e) \quad (13)$$

As stated by the second law of thermodynamics,

$$\begin{aligned} \frac{\dot{Q}_C}{T_c} - \frac{\dot{Q}_E}{T_e} &\leq 0 \\ \frac{\dot{Q}_C}{T_c} &= I_R \frac{\dot{Q}_E}{T_e} \end{aligned} \quad (14)$$

In which, I_R represents the parameter corresponding to internal irreversibility for evaporator-condenser assembly. $I_R = 1$ should be considered for the reversible cycles, and $I_R > 1$ for the irreversible cycles. Working fluid temperature ratio (x_R), total heat transfer surface area ($A_{T,R}$), and ratio of heat transfer surface area (a_R) for the evaporator-condenser assembly are given as below formulas:

$$x_R = \frac{T_e}{T_c} \quad (15)$$

$$a_R = \frac{A_C}{A_E} \quad (16)$$

$$A_{T,R} = A_C + A_E \quad (17)$$

Fig. 1. Generalized four-temperature-absorption refrigerator system [40].

T_c , T_e , $\dot{Q}_C$ and $\dot{Q}_E$ can be defined using Equations (12) and (13) to (14)–(17):

$$T_c = \frac{\mu T_C x_R a_R + \theta I_R T_E}{x_R (a_R \mu + I_R \theta)} \quad (18)$$

$$T_e = \frac{\mu T_C x_R a_R + \theta I_R T_E}{(a_R \mu + I_R \theta)} \quad (19)$$

$$\dot{Q}_C = \frac{\theta A_{T,R}}{1 + a_R} \left(\frac{I_R a_R \mu (T_E - T_C x_R)}{x_R (a_R \mu + I_R \theta)} \right) \quad (20)$$

$$\dot{Q}_E = \frac{\theta A_{T,R}}{1 + a_R} \left(\frac{a_R \mu (T_E - T_C x_R)}{(a_R \mu + I_R \theta)} \right) \quad (21)$$

2.3 Ecological function of the system

The evolved ecological function which includes the magnitudes of maximum energy destruction of the system, maximum output power for the heat engine, and maximum cooling load in the absorption cooling system is defined as following [35–40]:

$$E = \dot{Q}_E + \dot{Q}_G - \dot{Q}_A - T_o \left(\frac{\dot{Q}_A}{T_A} - \frac{\dot{Q}_G}{T_G} + \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_E}{T_E} \right) \quad (22)$$

2.4 Coefficient of performance of the system

The coefficient of performance of the absorption system can be formulated as following:

$$COP = \frac{\dot{Q}_E}{\dot{Q}_G} \quad (23)$$

3 Optimization process

3.1 Evolutionary algorithm: genetic algorithm

Genetic algorithms use a repetitive, random search method and the best answer and copy it in an easy way principle of biological evolution [41]. First parameter in an evolutionary algorithm would be the population of individuals. Individual expresses the values of the decision parameters and is a probable answer to the optimization issue [41]. More about genetic algorithm and its process could be find in references [41, 42].

3.2 Objective functions, decision parameters and limitations

The coefficient of performance (COP) and the ecological function (E) are two objective functions for this

Fig. 2. Pareto frontier (Pareto optimum answers) for E against COP employing NSGA-II.

work, which are identified by Equations (22) and (23). Four decision variables have been chosen in our study as follows :

- a_H : Ratio of heat transfer surface area
- a_R : Ratio of heat transfer surface area
- x_H : Hot working fluid temperature ratio
- x_R : Refrigerant working fluid temperature ratio

Albeit the decision parameters would be different in the optimization process, each should be in an appropriate interval. By considering following limitations the objective functions were unraveled:

$$2 \leq a_H \leq 2.5 \quad (24)$$

$$0.2 \leq a_R \leq 0.3 \quad (25)$$

$$0.85 \leq x_H \leq 0.95 \quad (26)$$

$$0.55 \leq x_R \leq 0.6 \quad (27)$$

4 Results and discussion

Utilizing multi-objective optimization on the basis of the NSGA-II method, both the coefficient of performance (COP) and the ecological function (E) are maximized at the same time. The objective functions in the performed optimization, and the limitations which have been used, are identified by Equations (22) and (23) and inequalities domains (24) and (27) respectively. The working fluid temperature ratios (x_H, x_R) and heat transfer surface area ratios (a_H, a_R) are assumed design parameters throughout the optimization process. Due to agreement with appreciated literatures, following characteristics of the refrigerating system are presumed as below [35–40]:

$$A_E = 150, A_G = 45, I_H = 1.05, I_R = 1.05, T_C = 313 \text{ (K)}, T_E = 288 \text{ (K)}, T_G = 393 \text{ (K)}, T_0 = 290 \text{ (K)}, \alpha = 2.3, \beta = 0.4, \mu = 3.265, \theta = 0.195, T_A = 315 \text{ (K)}.$$

Figure 2 demonstrates the frontier of optimum Pareto for objective functions E and COP , also optimal outcomes

of TOPSIS, LINMAP and FUZZY decision making techniques. The span of variations for optimum outcomes of E is from 689.2 to 950.7 (kW), and from 3.57 to 4.84 for COP .

Figures 3a–3d depict the variation of different magnitudes of decision parameters throughout their accepted span for the optimum design points on the front of Pareto. The variation of the a_H variable is illustrated in Figure 3a.

In Figure 3b, the blue line shows the greatest magnitude of a_R which is equal to 0.3. Figure 3c shows that the variation of different magnitudes of x_H for the optimum design points on the front of Pareto changes from 0.85 to 0.8501. The variation of x_R for the optimal points on the front Pareto is depicted in Figure 3d.

Table 1 shows the optimum outcomes gained for objective functions and decision variables employing Fuzzy Bellman-Zadeh, TOPSIS and LINMAP techniques. Table 1 demonstrated outcomes obtained from aforementioned decision making techniques for four-temperature-level absorption refrigerators and results exhibited by [40]. A deviation index which characterizes the error of each result from the ideal result has been defined to compare the result of the single objective-single parameter study (Ref. [40]) with various solutions in our work.

$$d_+ = \sqrt{(COP_n - COP_{n,ideal})^2 + (E - E_{n,ideal})^2} \quad (28)$$

$$d_- = \sqrt{(COP_n - COP_{n,non-ideal})^2 + (E - E_{n,non-ideal})^2} \quad (29)$$

$$d = \frac{d_+}{(d_+) + (d_-)} \quad (30)$$

COP_n and E_n stand for Euclidian non-dimensionalized normalized thermal efficiency and output power (indexes *ideal* and *non-ideal* denote the relevant magnitudes of objective functions at the ideal and non-ideal points, correspondingly). As it is presented in Table 1 the deviation indexes for the multi-objective optimization are 0.148,

Fig. 3. (a) The distribution of a_H for the optimum points on Pareto front. (b) The distribution of a_R for the optimum points on Pareto front. (c) The distribution of x_H for the optimum points on Pareto front. (d) The distribution of x_R for the optimum points on Pareto front.

Table 1. Decision making of multi-objective optimal solutions.

Decision making method	Decision variables				Objective functions		Deviation index from the ideal solution (d)
	a_H	a_R	x_H	x_R	COP	E (kW)	
TOPSIS	2.00	0.30	0.85	0.591	4.3218	911.955	0.148175
LINMAP	2.00	0.30	0.85	0.588	4.360	899.083	0.197395
Bellman Zadeh	2.00	0.30	0.85	0.581	4.444	869.399	0.310903
Ideal Point	—	—	—	—	4.840	950.700	0.000000
Non-ideal Point	—	—	—	—	3.570	689.200	∞
Reference [40]	2.41	0.25	0.87	0.58	2.5	680.000	0.966918

0.197 and 0.311 for results gained by TOPSIS, LINMAP and Bellman Zadeh decision making techniques, correspondingly. These magnitudes are compared with the relevant magnitudes achieved for the sole objective-single parameter optimization (Ref. [40]) which the index of deviation is 0.967. This means that the multi-objective-multi variable optimization for all decision makers have lower deviation indexes than the sole objective-single parameter optimization.

The TOPSIS decision-making method has achieved to the minimum magnitude for index of deviation, therefore the result which is chosen employing the TOP-

SIS decision-making is chosen as an ultimate desired optimum result of the multi objective-multi parameter optimization for the four-temperature-level absorption refrigerators.

Finally, to determine deviation of the employed methods, error analysis is used. Error analysis is performed according to average absolute relative deviation (AARD) and maximum absolute relative deviation (MARD) of the outcomes obtained from each decision making methods. It should be noted that, error analysis is applied on the final solutions which gained after 30 runs of aforementioned

Table 2. Analysis of error for used decision makers.

Error	TOPSIS		LINMAP		Fuzzy	
	<i>COP</i>	<i>E</i>	<i>COP</i>	<i>E</i>	<i>COP</i>	<i>E</i>
Max error %	1.44	1.99	0.58	0.35	2.44	4.95
Average error %	0.89	1.16	0.23	0.20	0.92	1.89

decision makers. Table 2 summarized outcomes of error analysis for each decision making approach.

5 Conclusions

With the aim of evolved ecological function, the optimization of irreversible absorption refrigerator with four-temperature-levels has been carried out. A balance between entropy production and the load supplied to the system and cooling load has been established. The effects of x_H , a_R , x_R , and a_H factors and temperature of operation fluids on the aforementioned system are analyzed.

The ecological function (E) and the coefficient of performance (COP) are simultaneously assumed for multi-objective optimization. The ratio of working fluid temperatures (x_H, x_R) and ratio of heat transfer surface areas (a_H, a_R) have been presumed as design variables. The multi objective evolutionary algorithm on the basis of the NSGA-II method has been utilized and the frontier of optimum Pareto throughout the objectives space was specified. To specify an ultimate solution from the results gained by multi-objective optimization process, three well-known decision making techniques have been implemented and final outcomes are compared on the basis of error analysis.

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