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Multi-objective optimization of compression refrigeration cycle of Unit 132 South Pars refineries

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ABSTRACT

The purpose of this paper is multi-objective optimization of refrigeration cycle by optimization of all components of the cycle contains heat exchangers, air condenser, evaporator and super-heater. Studied refrigeration cycle is compression refrigeration cycle of unit 132 Third refineries in south pars that provide chilled water for cooling refinery equipment's. Cycle will be performed by the genetic algorithm optimization. Thermodynamic purpose of the cycle Expressed by minimization of Exergy destruction or maximization or coefficient of performance (C.O.P), economic purpose of the cycle Expressed by minimization of cold water production cost by TRR method and environmental purpose of the cycle Expressed by minimization of NOx, CO2 and CO Which is produced by power consumption. Combination of objectives and decision variables with suitable engineering and physical constraints makes a set of the MINLP optimization problem. In EES software. Optimization programming is performed using NSGA-II algorithm. Four optimization scenarios including the thermodynamic single-objective, the economic single-objective, environmental single-objective by power electricity consumption and multi-objective optimizations are performed. The output of the multi-objective optimization is a Pareto frontier that yields a set of optimal points that the final optimal solution has been selected using two decision-making approaches including the LINMAP and TOPSIS methods.. It was shown that the best results in comparison to the simple cycle reduction in Exergy destruction from 264.8 kW to 127.6 kW(Increased coefficient of performance from 3.872 to 7.088), reduction in cold water production cost from 117.5 dollar/hour to 87.19 dollar/hour and reduction in NOx emission from 4958 kg/year to 2645 kg/year.

Keywords: Compression Refrigeration Cycle, Multi-Objective Optimization, Genetic Algorithm (GA), TOPSIS and LINMAP Decision-Making.

1. Introduction

In selecting the design and energy optimizing systems, several and commonly conflicting criteria may be considered. For example, for the optimization of a vapour compression refrigeration system, a designer may consider one or more of the thermodynamic, economic and environmental criteria as the objective function. If only the thermodynamic criterion

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is considered, the system will be an ideal system from a thermodynamic point of view, but it might not be able to pass the economic and environmental criteria. On the other hand, by considering only the economic criterion, the system will be the cheapest one, but may not be a well-designed one from the thermodynamic and environmental points of view, as the system might consume a lot of energy or emit a lot of pollutants into the environment. None of these systems are acceptable from a comprehensive engineering point of view. Thus, it seems that a simultaneous consideration of all or some of these criteria might provide a better option for engineers. This goal can be achieved by multi-objective optimization techniques. In this way, we will have a system that satisfies all the optimization criteria as much as possible. Thermodynamic criteria are usually the first law (energetic) and the second law is the exergetic criteria. In this paper, the second law criterion (the total exergy destruction of the system) is considered, as the thermodynamic objective function, which has been proven that it better takes into account the thermodynamic criterion than the first law optimization. The economic objective function is the total product cost of the system that is developed according to the total revenue requirement (TRR) method and environmental objective function is the total product NOx emission by cycle of electricity consumption. These three criteria are considered in a multi-objective optimization of a vapour compression refrigeration system as an example of energy systems. As a powerful thermodynamic tool, the exergy analysis (availability or second law analysis) presented in this study is well suited for furthering the goal of a more effective energy resource use, for it enables the determination of location, cause, and true magnitude and waste and loss of exergy. This information can be used in the design of new energy-efficient systems, and for increasing the efficiency of the existing system (Bejan et al., [1]). There have been several studies on the exergy analysis of different types of refrigeration and heat pump systems. Leidenfrost et al. [2] used exergy analysis to investigate the performance of a refrigeration cycle, working with R-12 as the refrigerant. Dincer et al. [3] investigated the thermal performance of a solar powered absorption refrigeration system. Meunier et al. [4] studied the performance of adsorptive refrigeration cycles using the second law analysis. Nikolaidis and Probert [5] utilized the exergy method in order to simulate the behaviour of a two-stage compound compression-cycle with flash inter-cooling run with R-22 as the refrigerant. The effects of temperature changes in the condenser and evaporator on the irreversibility rate of the cycle were determined. Bouronis et al. [6] studied the thermodynamic performance of a single-stage absorption/compression heat pump, using the ternary working fluid, trifluoroethanol water-tetraethyleneglycol dimethylether, for upgrading waste heat. Go¨ktun and Yavuz [7] investigated the effects of thermal resistance and internal irreversibilities of the performance of combined cycles for cryogenic refrigeration. Chen et al. [8] studied the optimization of a multi-stage endoreversible combined refrigeration system. Kanoglu [9] presented a methodology for the exergy analysis of multi-stage cascade refrigeration cycle and obtained the minimum work in relation to the liquefaction of natural gas. Yumrutas, et al. [10] presented a computational model based on exergy for the investigation of the effects of the evaporation and condensation temperatures on pressure losses, exergy losses, second law efficiency, and the coefficient of performance (COP) of a vapour compression refrigeration cycle. Kanoglu et al. [11] developed a procedure for the energy and exergy analyses of open- cycle desiccant cooling systems and applied it to an experimental unit operating in the ventilation mode with natural zeolite as the desiccant. Kopac and Zemher [12] presented a computational study based on the exergy analysis, investigating the effects of the saturated temperatures of the condenser and the evaporator on the efficiency defects in each of the plant components, the total efficiency defect of the plant, the second law efficiencies and the values of COP of a vapour compression refrigeration plant for NH3, HFC-134a, R-12 and R-22. Ozgener and Hepbasli [13] reviewed the energy and exergy analyses of solar-assisted heat pump systems, many of which were in the category of solar-assisted, ground-source heat pump systems. On the other hand, there have been several studies on the economic or thermoeconomic analysis of refrigeration and heat pump systems. d'Accadia and de Rossi [14] investigated the thermoeconomic optimization of a vapour compression refrigerator using the exergetic cost theory method. Dingec and Ileri [15] carried out the optimization of a domestic R-12 refrigerator. The structural coefficient method was used in this optimization procedure. Their objective was to minimize the total life cycle cost, which included both electricity and capital costs for a given cooling demand and system life. Tyagi et al. Sanaye and Malekmohammadi [16] presented a new method of thermal and economic optimum design of air conditioning units with vapour compression refrigeration system. Selbas et al. [17] applied an exergy-based thermoeconomic optimization application to a sub-cooled and superheated vapour compression refrigeration system. All calculations were made for three refrigerants: R-22, R-134a, and R-407c. Misra et al. [18] investigated the thermoeconomic optimization of single- and double-effect H2O/LiBr vapour-absorption refrigeration systems. Sanaye and Niroomand [19] investigated the thermal-economic modelling and optimization of a vertical ground source heat pump. As mentioned above, there have been comprehensive investigations in the field of exergy, and economic analyses and optimization of refrigeration and heat pump systems, especially on vapour compression refrigeration systems. But, as mentioned earlier, the consideration of only one of the exergetic or economic criterion as the objective function of optimization would not help the systems satisfactorily pass the other criteria. Thus, it seems, a multi-objective optimization is needed. Multi-objective optimization, developed to deal with different and often competing objectives, poses an optimization challenge (e.g., see Fonseca and Fleming, [20]; Van Veldhuizen and Lamont, [21]; Deb, [22] and Konak et al. [23]). Recent researchers have paid a lot of attention to multi-objective optimization of energy systems (e.g., Toffolo and Lazzaretto, [24], [25]). Moreover, Sayyaadi et al. [26] and Sayyaadi and Amlashi [27] performed multi-objective optimization for GSHP systems in the cooling mode.

Objective functions were the total product cost of the system and the total exergy destruction. Sayyaadi and Nejatolahi [28] performed multi-objective optimization of a cooling-tower-assisted vapour compression refrigeration system. They compared the results of exergy and thermoeconomic analyses of the base case—two single-objective-optimized, and a multi-objective-optimized systems.

The present work has been presented as an attempt for multi-objective optimization of a vapour compression refrigeration system. Objectives are reductions in the total exergy destruction, the total product cost of the system, and production of NOx. A product in the refrigeration system is defined as the refrigeration effect of the evaporator; hence, in our study, the cost of the system product is defined as the unit cost of refrigeration effect on the evaporator. Four optimization scenarios including the thermodynamic single-objective, thermoeconomic single-objective, environmental single-objective and multi-objective optimizations are explored in this work. All optimization scenarios are conducted using an artificial intelligence technique known as evolutionary algorithm (EA). The output of the multi-objective optimization is a Pareto frontier yielding a set of optimal points. In the case of the multi-objective optimization scenario, two decision-making approaches, including the LINMAP [29, 30] and TOPSIS [29, 30] were utilized for selecting a final optimum solution.

2.System specification

A vapour compression refrigeration system with the cooling load of 1631 kW (463.75 Ref. Ton) is considered as illustrated in Fig. 1. A scroll compressor is used to drive the system with R-134a as a refrigerant. The super-heater and evaporator are shell and tube heat exchanger in which the refrigerant is placed in the shell side and water flows in the tube side. In this cycle, an air condenser is used and the condenser is a tube-fin heat exchanger. The water inlet and outlet temperatures in the evaporator are 40 C and 30 C respectively. The shell and tube heat exchangers (the evaporator and super-heater) and air condenser are designed, based on the procedure given by Coulson and Richardson [31], and Ludwing [32], respectively.

3.Thermodynamic modelling

Thermodynamic model of the entire cycle is built on the following basic assumptions:

a) All processes have a steady state and steady flow with negligible potential and kinetic energy effects.
b) The directions of heat transfer to the system and work done on the system are positive.
c) Heat transfer and refrigerant pressure drops in the pipeline are ignored.
d) No chemical reaction occurs.

Thermo – hydraulic modelling of the heat

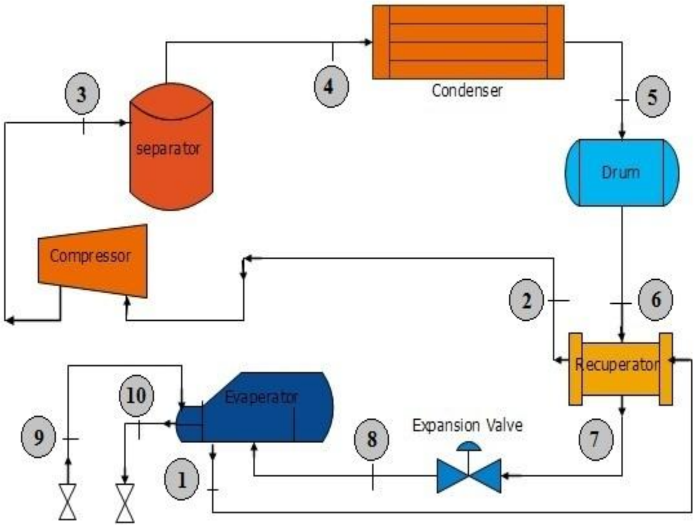

Fig. 1. Schematic arrangement of a vapour compression refrigeration system

exchangers is performed using the modified heat transfer analysis and ε-NTU method in order to estimate the heat exchangers area.

4.Exergy analysis

An exergy analysis provides, among other things, the exergy of each stream in a system as well as the real 'energy waste' i.e., the thermodynamic inefficiencies (exergy destruction and exergy loss), and the exergetic efficiency for each system component (Bejan et al., 1996) Thermodynamic processes are governed by the laws of conservation of the mass and energy. However, exergy is not generally conserved but is destroyed by irreversibilities within a system. Further, exergy is lost, in general, when the energy associated with a material or the energy stream is lost to the environment. The general form of the exergy balance for a control volume in steady state conditions is:

$$\dot{I} = \dot{E}^i - \dot{E}^o + \dot{E}^Q + \dot{E}^W \quad (1)$$

where $\dot{I}$ is the total exergy destruction or irreversibility. The $\dot{E}^Q$ is the exergy flow associated with the heat transfer through the control volume boundaries and is calculated as follows:

$$\dot{E}^Q = \dot{Q}(1 - \frac{T_0}{T}) \quad (2)$$

Since the work is an ordered energy, its associated exergy flow is equal to the amount of that work. Thus

$$\dot{E}^W = \dot{W} \quad (3)$$

The $\dot{E}^i$ and $\dot{E}^o$ are the exergies of the control volume inlet and outlet streams of matter and are given by:

$$E = \dot{m}\varepsilon \quad (4)$$

where ε is the specific exergy of a steam of matter that includes kinetic (ε^K), potential (ε^P), physical (ε^{Ph}) and chemical (ε^{Ch}) exergies:

$$\varepsilon = \varepsilon^K + \varepsilon^P + \varepsilon^{Ch} + \varepsilon^{Ph} \quad (5)$$

$$\varepsilon^K = \frac{V_0^2}{2} \quad (6)$$

$$\varepsilon^P = gH_0 \quad (7)$$

The kinetic and potential exergies are ignored in this work. Further, since most material streams of the system are not associated with any kind of chemical reaction, the chemical exergy terms will be cancelled out in the balance equation. Thus, the exergy of flow in this work comprised only the physical components. The physical-specific exergy is given by:

$$\varepsilon^{Ph} = (h - T_0 s) - (h_0 - T_0 s_0) \quad (8)$$

where the subscript 0 refers to the environmental conditions (restricted equilibrium with the environmental). The specific chemical exergy for liquid and vapour forms of water are equal to 2.4979 and 0 kJ kg1, respectively (Bejan et al., 1996). Application of the exergy balance equation for each component of the vapour compression refrigeration system (Fig. 1) leads to the balancing equations mentioned in Table 1.

5.Economic models

The economic model takes into account the cost of the components, including amortization and maintenance, and the cost of electricity consumption. In order to define a

Table 1. Exergy balance equations for each component of the refinery compression refrigeration cycle (Fig. 1)

$$\dot{I}_{comp} = \dot{m}_{R134a}[T_0(s_3 - s_2)]$$

$$\dot{I}_{cond} = \dot{m}_{R134a} \times T_0 \times \left[\frac{(h_4-h_5)}{T_5} - (s_4 - s_5)\right] + \dot{W}_{Fan}$$

$$\dot{I}_{evp} = \dot{m}_{R134a} \times [(h_1 - h_8) - T_0(s_1 - s_8)] - \dot{m}_{water} \times [(h_9 - h_{10}) - T_0(s_9 - s_{10})]$$

$$\dot{I}_{ex.v} = \dot{m}_{R134a}[T_0(s_8 - s_7)]$$

$$\dot{I}_{sup} = \dot{m}_{R134a} \times \left[[(h_6 - h_7) - T_0(s_6 - s_7)] - [(h_2 - h_1) - T_0(s_2 - s_1)]\right]$$

$$\dot{I}_{total} = \dot{I}_{comp} + \dot{I}_{gc} + \dot{I}_{evp} + \dot{I}_{ex.v} + \dot{I}_{eje}$$

a cost function, which depends on the optimization parameters of interest, component costs have to be expressed as functions of thermodynamic variables. These relationships can be obtained by statistical correlations between costs and the main thermodynamic parameters of the component performed on a real data series.

Based on the estimated total capital investment and assumptions of economic, financial, operating, and market input parameters, the total revenue requirement is calculated on a year-by-year basis. Finally, the non-uniform annual monetary values associated with the investment, such as operating, maintenance, and fuel costs of the system are levelized after being analysed; that is, they are converted to an equivalent series of constant payments (annuities) (Bejan et al., [1]). The annual total revenue requirement (TRR, total product cost) for a system is the revenue that must be collected in a given year through the sale of all products to compensate the system operating company for all expenditures incurred in the same year and to ensure a sound economic system operation (Bejan et al., [1]).

The series of annual costs associated with the carrying charges CC_j and expenses (FC_j and OMC_j) for the jth year of a system operation is not uniform. In general, carrying charges decrease while fuel costs increase with an increase in the number of years of operation (Bejan et al., [1]). A levelized value for the total annual revenue requirement, TRR_L, can be computed by applying a discounting factor and the capital-recovery factor CRF:

$$TRR_L = \mathrm{CRF} \times \sum_{j=1}^{BL} \frac{TRR_j}{(1 + i_{eff})^j} \quad (9)$$

in applying Eq. (9), it is assumed that each monetary transaction occurs at the end of each year. The capital-recovery factor, CRF, is given by:

$$\mathrm{CRF} = \frac{i_{eff}(1 + i_{eff})^n}{(1 + i_{eff})^n - 1} \quad (10)$$

TRR_j is the total revenue requirement in the jth year of system's operation, i_{eff} is the average annual effective discount rate (cost of money), and n denotes the system's economic life expressed in years. In the case of the vapour compression refrigeration system, the annual total revenue requirement is equal to the sum of the following four annual amounts including the total capital-recovery (TCR); minimum return on investment (ROI); fuel costs (FC) and the operating and maintenance cost (OMC):

$$TRR_j = TCR_j + ROI_j + FC_j + OMC_j \quad (11)$$

The calculation method for TCR_j and ROI_j is given by Bejan et al. [1]), the extension of TCR_j and ROI_j for a cooling system is developed by Sayyaadi et al.[26], Sayyaadi and Amlashi [27] and Sayyaadi and Nejatolahi [28]. FCj and OMCj and heir corresponding levelized values are obtained using the following procedure. If the series of payments for the annual fuel cost FC_j is uniform over the time except for a constant escalation r_{FC} (i.e., $FC_j = FC_0(1+ r_{FC})^j$), then the levelized value FC_L of the series can be calculated by multiplying the fuel expenditure, FC_0, at the beginning of the first year by the constant escalation levelization factor CELF:

$$FC_L = FC_0.\mathrm{CELF} = FC_0 \times \frac{k_{FC}(1 - k_{Fc}^n)}{(1 - k_{FC})} \times CRF \quad (12)$$

where,

$$k_{FC} = \frac{1 + r_{FC}}{1 + i_{eff}} \quad (13)$$

The terms r_{FC} and CRF denote the annual escalation rate of the fuel cost and the capital-recovery factor, respectively. The levelized annual operating and maintenance costs (OMC_L) are given as follows:

$$OMC_L = OMC_0 \times \text{CELF} = OMC_0 \frac{k_{OMC}(1-k_{OMC}^n)}{(1-k_{OMC})} \quad (14)$$

with

$$k_{OMC} = \frac{1 + r_{OMC}}{1 + i_{eff}} \quad (15)$$

The term r_{OMC} is the nominal escalation rate of operating and maintenance costs.

Finally, the levelized carrying charges, CC_L, are obtained from the following equation:

$$CC_L = TRR_L - FC_L - OMC_L \quad (16)$$

The annual carrying charges or capital investment (superscript CI) and operating and maintenance costs (superscript OMC) of the total system can be apportioned among the system components according to the contribution of the kth component to the purchased equipment cost for the overall system (=$\text{PEC}_{total} = \sum_k \text{PEC}_k$):

$$\dot{Z}_k^{CI} = \frac{CC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad (17)$$

$$\dot{Z}_k^{OM} = \frac{OMC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad (18)$$

Here, PEC_k and τ denote the purchased equipment cost of the kth system component and the total annual time (in hours) of system operation at full load, respectively. PEC equations for various components of the vapour compression refrigeration system are given in Table 2. [33, 34].

It must be mentioned that all costs are modified to the cost index of 2014 as follows (Bejan et al., 1996):

$$\dot{Z}_{new} = \dot{Z}_{ref} (\frac{I_{new}}{I_{ref}}) \quad (19)$$

$\dot{Z}_{new}$ and $\dot{Z}_{ref}$ are the renewed cost and cost at reference year for the proposed equipment. I_{new} and I_{ref} are cost indexes at new and reference years, respectively. In this work Marshall and Swift index is used for equipment as indicated in the Table 3 (Peters and Timmerhaus, 1991) (indexes of years after 1991 was obtained in this reference by forecasting).

Table 3. Marshall and Swift index in various years (Peters and Timmerhaus, 1991)*

year	index
1990	915
1995	1027.5
1996	1039
1997	1056.8
1998	1061.9
1999	1068.3
2000	1089
2001	1092
2002	1100.2
2003	1109
2004	1115.6
2005	1129.6
2006	1143
2007	1156.6
2009	1170.2
2010	1194.8
2011	1242.6
2012	1256.3
2013	1267.6
2014	1286.6

*Marshall & Swift/Boeckh, Marshall Valuation Service, Quarterly Cost Index

Table 2. equipment cost of each component of the refinery compression refrigeration cycle (Fig. 1)

$$\dot{Z}_{compressor} = (\frac{573\dot{m}_{ref}}{0.8996 - \eta_{isen}})(\frac{P_{cond}}{P_{evp}})ln(\frac{P_{cond}}{P_{evp}})$$

$$\dot{Z}_{sup} = 2290(A_{sup})^{0.6}$$

$$\dot{Z}_{cond} = 516.621A_{cond} + 268.45$$

$$\dot{Z}_{evp} = 309.143A_{evp} + 231.915$$

The term $\dot{z_k}$ represents the cost rate associated with the capital investment and operating and maintenance expenses:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \quad (20)$$

The annual fuel and cooling water costs for the first year of the system's operation are given as follows respectively:

$$FC_0 = C_{elect}.\tau.\dot{W}_{tot} \quad (21)$$

In which, C_{elect} is the electricity price per kWh, $\dot{W}_{tot}$ is the total power consumption of the system (Eq.(21)). The electricity cost is in local Iranian prices considered as 63.75 \$ $MW^{-1}h^{-1}$ respectively. The operating life of the system is assumed as 25 years. The total annual operating time of the system in the cooling mode is considered as 4,380 h. In this study, the magnitude of other economic constants such as r_{FC}, ieff and r_{OMC} are assumed to be 0.156, 0.2 and 0.156, respectively. The levelized cost rates of electricity expenditures for the system are given as follows:

$$\dot{Z}_{Elec} = \frac{FC_L}{\tau} \quad (22)$$

Levelized costs, such as $\dot{Z}_k^{CI}$; $\dot{Z}_k^{OM}$ and $\dot{Z}_{Elec}$ are used as input data for the economic analysis.

6.Emission modelling

No combustion reaction occurs in the compression refrigeration cycle, and, hence, does not directly cause any environmental emission in the cycle. But since the cycle works on electric energy, and electricity is generated by power plants, and power plants emit pollutants for power generation, we can consider emission production based on electricity consumption. Table 4 shows the production of various pollutants in terms of grams per kilowatt hour of electricity.

The determination of the amount of pollutants produced by the refrigeration cycle in a year is obtained from the following equation:

$$m_{CO_2} = \tau \times (\dot{W}_{com} + \dot{W}_{fan}) \times fac_{CO_2}$$

$$m_{NO_x} = \tau \times (\dot{W}_{com} + \dot{W}_{fan}) \times fac_{NO_x}$$

$$m_{CO} = \tau \times (\dot{W}_{com} + \dot{W}_{fan}) \times fac_{CO} \quad (23)$$

where m_{CO_2} and xco are m_{NO_x} and m_{CO} emission in kg/year, respectively. τ, the total annual operating time of the system in the cooling mode is considered to be 4,380 h, fac_{CO_2}, fac_{NO_x} and fac_{CO} are factor of pollutants obtained from Table 4.

7.Objective function, decision variables and constraints

Optimization problems usually involve these elements: objective functions, decision variables, and constraints. Following sections describe the element of optimization problem for the proposed refinery compression refrigeration system.

7.1.Objective functions

Objective functions for single-objective and multi-objective optimizations in this study are the thermodynamic, economic, and environmental objective functions, denoted by Eq. (24) to (26), respectively. In the single-objective of thermodynamic optimization, the aim is minimizing the total irreversibility of the compression refrigeration system. In the single-objective of economic optimization, the total product cost of the compression refrigeration system is minimized. In the single-objective pertaining to environmental optimization, the total product containing NOx, CO and CO_2 of the compression refrigeration system driven by electricity is minimized.

Thermodynamic:

$$I_{total} = I_{comp} + I_{cond} + I_{evp} + I_{ex.v} + I_{HEX} \quad (24)$$

Economic:

$$\dot{C}_P = \dot{C}_F + \sum \dot{Z}_k \quad (25)$$

Environmental:

$$\begin{cases} m_{CO_2} = \tau \times (\dot{W}_{com} + \dot{W}_{fan}) \times fac_{CO_2} \\ m_{NO_x} = \tau \times (\dot{W}_{com} + \dot{W}_{fan}) \times fac_{NO_x} \\ m_{CO} = \tau \times (\dot{W}_{com} + \dot{W}_{fan}) \times fac_{CO} \end{cases} \quad (26)$$

7.2.Decision variables

The following four decision variables have been chosen for this work:

Table 4. Factor of pollutants in power plant for production of electricity[35]

	NOx	CO_2	CO
Pollutants(gr/ kW.hr)	2.625	719.468	0.675

1- T_{evap}: the evaporator saturation temperature
2- $N_{t,sup}$: tube number of super-heater
3- n_{fan}: fan speed in the condenser
4- P_{cond}: the condenser saturation pressure

7.3.Constraints

In engineering applications of the optimization problem, there are usually certain constraints on the trading-off of decision variables. In this case, some limitations emanate from a technical view point. For example, the allowable water velocity in the tube sides of a shell and tube heat exchanger should be within the range of 1–3 m/s to prevent fouling and erosion, respectively. The recommended good practice value for LD (ratio of the tube length to the shell diameter) for the evaporator and condenser is a number between 5 and 15. Limitations on the maximum and minimum ranges of decision variables can be obtained as follows:

$$T_{evap} < 30\ °C \tag{27}$$

$$N_{t,HEX} \leq 500 \tag{28}$$

$$1400\ kPa \leq P_{cond} \tag{29}$$

$$60\ rpm \leq n_{fan} \leq 219\ rpm \tag{30}$$

$$W_{max,com} \leq 450\ kW \tag{31}$$

$$0.2 \leq D_{s,HEX} \leq 1.2\ m \tag{32}$$

$$0.2 \leq D_{s,evap} \leq 1.2\ m \tag{33}$$

$$\Delta T_{min,HEX}\ , \Delta T_{min,evap} \geq 1 \tag{34}$$

$$\Delta T_{min,cond} \geq 17 \tag{35}$$

8.Multi-objective optimization

Multi-objective optimization of objective functions, expressed by Eq (24) and (26), is performed using the multi-objective evolutionary algorithm. A multi-objective optimization problem requires the simultaneous satisfaction of a number of different and often conflicting objectives. It must be mentioned that no combination of decision variables can optimize all objectives simultaneously. Multi-objective optimization problems generally show a possibly an uncountable set of solutions; whose evaluated vectors represent the best possible trade-offs in the objective function space. Pareto optimality is the key concept to establish a hierarchy among the solutions of a multi-objective optimization problem, in order to determine whether a solution is really one of the best possible trades-off [36] Eq. (36) shows how a multi objective optimization problem can be formulated mathematically.

$$\min F_j(X)\ \ \forall j \in \{1,2,3, \ldots., k\}\ \ subject\ to\ X \in L \tag{36}$$

where we have $k \geq 2$ objective functions $F_j: R^n \to R^1$. The feasible objective region Z is the image of the feasible region ($i.e\ Z = F(X) \subset R^k$). The elements of Z are called objective vectors. The objective vectors are denoted by *F(X)* or by $Z = [z_1, z_2, z_3, \ldots, z_k]^T$, where $z_j = F_j(X)\ \forall j \in \{1,2,3, \ldots., k\}$ [37].

Classical search and optimization methods are not efficient in following the Pareto approach for multi-objective optimizations. The class of search algorithms that implement the Pareto approach for multi-objective optimization in the most straightforward way is the class of multi-objective evolutionary algorithms (MOEAs). In this paper, one of most powerful MOEA, namely, the Non-dominated sorting genetic algorithm, NSGA-II, has been employed to find the Pareto optimal frontier for the proposed recuperative gas cycle. This method was well described by Sayyaadi et al. in [26].

9.Decision-making in the multi-objective optimization

In multi-objective optimization, a process of decision-making for the selection of the final optimal solution from available solutions is required. There are several decision-making processes in resolving the decision problem. Two methods can be employed in decision-making for the selection of a final optimal solution from the Pareto frontier, which is obtained, for example, by the NSGA-II. Since, dimension of various objectives in a multi-objective optimization problem might be different, before any decision, dimension and scales of objectives space should be unified. In this regard, objective vectors should be non-dimensionalized before decision-making by Euclidian non-dimensionalization method.

- Euclidian non-dimensionalization

In this method, a non-dimensionalized objective, F_{ij}^n , is defined as,

$$F_{ij}^{n} = \frac{F_{ij}}{\sqrt[2]{\sum_{i=1}^{m}(F_{ij})^2}} \quad for\ minimizing\ and\ maximizing\ object \tag{37}$$

In this paper, most famous and common type of decision-making processes including the LINMAP and TOPSIS methods are simultaneously used, and the final optimal solution has been decided, based on engineering experience and criteria in solutions suggested by these two methods. LINMAP and TOPSIS employ Euclidian non-dimensionalization. The following sections are presented here to describe these decision-making algorithms.

9.1.LINMAP decision-making method

An ideal point on the Pareto frontier is the point in which each objective is optimized, regardless of the satisfaction of other objectives. It is clear that, in the multi-objective optimization, it is impossible to have each objective in its optimal condition, which can be achieved in a single-objective optimization. Therefore, the ideal point is not located on the Pareto frontier. In the LINMAP method, after Euclidian non-dimensionalization of all objectives, the distance of each solution on the Pareto frontier from the ideal point denoted by d_{i+} is determined as follow,

$$d_{i+} = \sqrt[2]{\sum_{j=1}^{n}\left(F_{ij} - F_j^{Ideal}\right)^2} \tag{38}$$

where n denotes the number of objective, while i stands for each solution on the Pareto frontier (*i=1,2,….,m*). In Eq. (38), F_j^{Ideal} is the ideal value for j^{th} objective obtained in a single-objective optimization. In LINMAP method, the solution with minimum distance from ideal point is selected as a final desired optimal solution. Hence, i index for a final solution, $i_{final,}$ is,

$$i_{final} \equiv i \in \min(d_{i+})\ \ i = 1,2,\ldots,m \tag{39}$$

9.2.TOPSIS decision-making method

In this method, beside the ideal point, a non-ideal point is defined also. The non-ideal point is the ordinate in objectives space in which each objective has its worst value. Therefore, besides the solution distance from ideal point,d_{i+}, the solution distance from the non-ideal point denoted by d_{i-} is used as a criterion for the selection of the final solution. Hence,

$$d_{i-} = \sqrt[2]{\sum_{j=1}^{n}\left(F_{ij} - F_j^{Non-ideal}\right)^2} \tag{40}$$

In continuing the TOPSIS method a Cl_i parameter is defined as follows,

$$Cl_i = \frac{d_{i-}}{d_{i+} + d_{i-}} \tag{41}$$

In the TOPSIS method a solution with minimum Cl_i is selected as a desired final solution, therefore, if $i_{final,}$ is index for the final selected solution, we have,

$$i_{final} \equiv i \in \max(Cl_i)\ \ i = 1,2,\ldots,m$$

10.Results and discussion

The proposed model for the compression refrigeration system, schematically shown in Fig. 1, including four decision variables and their constraints (introduced in Section 7.3) is optimized using the NSGA-II algorithm. Four optimization scenarios including thermodynamic single-objective, economic single-objective, and environmental single-objective and multi objective optimizations are performed.

The final optimal solution in single-objective optimization is unique, but the final results in the multi-objective optimization set of Pareto optimal frontiers are shown in Fig. 2.

The final optimal solution has been selected using two decision-making approaches including the LINMAP and TOPSIS methods. As is clear, TOPSIS and LINMAP selected the same final optimal solution.

Optimization results in all four scenarios are indicated in Table 5.

Table 6 indicates the results of energy analysis for various designs. Some useful data are listed in this table, such as flow rates, heat loads, electrical works, and COPs. By comparing the results presented in Table 6 It can be seen that an improvement in the COP cycle occurs in the thermodynamic single-objective.

Exergy analysis for existing cycle and optimizations cycle with different objectives, are given in Table 7.

As expected, and as shown in Table 7, the maximum decrease in exergy destruction has occurred in thermodynamic single-objective optimization.

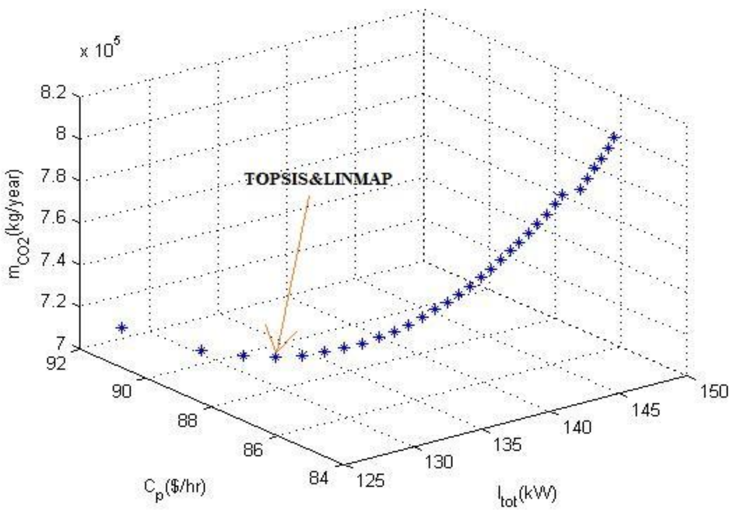

Fig. 2. Pareto optimal frontier in the multi-objective optimization

Table 5. The values of decision variables in the various optimization scenarios

Decision variables	Base case	Thermodynamic optimized	Economic optimized	Environmental optimized	Multi-objective optimized
T_{evap} (°C)	24	28.5	27.1	28.4	28.26
P_{cond} (kPa)	1750	1402	1401	1402	1400
$N_{t,HEX}$	170	382	450	382	450
n_{fan} (rpm)	219	60.16	64.53	60.17	60
$r_{p,comp}$	2.708	1.9	1.978	1.9	1.91
$D_{s,sup}$ (m)	0.3143	0.4711	0.5113	0.4711	0.5113
$N_{t,evap}$	270	1729	576	1510	1065
$D_{s,evap}$ (m)	0.4576	1.158	0.6688	1.082	0.909
$\Delta T_{min,evap}$(°C)	6	1.5	2.903	1.5	1.74
$\Delta T_{min,HX}$(°C)	27.71	15.55	16.02	15.55	15.28
$\Delta T_{min,cond}$(°C)	33.61	17.23	17.83	17.24	17.14

Table 6. The results of energy analysis the various optimization scenarios

Decision variables	Base case	Thermodynamic optimization	Economic optimization	Environmental optimization	Multi-objective optimization
Total refrigerant flow rate (kg/s)	12.39	11.07	11.06	11.07	11.04
Evaporator heat load (kW)	1631	1631	1631	1631	1631
Condenser heat load (kW)	2002	1842	1857	1843	1844
Super-heater heat load (kW)	124	96.25	105.6	96.29	101
Fan power (kW)	60	16.48	17.68	16.48	16.44
Compressor power (kW)	371.2	211.7	226.3	211.8	213.6
Thermodynamic cycle COP	3.782	7.147	6.685	7.144	7.088
COP improvement	-	88.97%	76.76%	88.89%	87.41%

As expected, and as shown in Table 7, the maximum decrease in exergy destruction has occurred in thermodynamic single-objective optimization.

Also exergy analysis for existing cycle and optimization cycle with different objectives has been shown in Fig. 3. The results of economic analysis for four optimized systems and the base case system are given in Fig. 4. It shows a comparison of the levelized costs including capital investment, maintenance cost, and electricity cost, for various designs of the compression refrigeration system.

Table 7. The re of exergy analysis the various optimization scenarios

	Base case		Thermodynamic optimization		Economic optimization		Environmental optimization		Multi-objective optimization	
Equipment's	I (kW)	δ	I (kW)	δ	I (kW)	δ	I (kW)	δ	I (kW)	δ
Evaporator	58.15	22%	33.75	26.87%	41.28	29.44%	33.75	26.86%	35.03	27.46%
Super-heater	13.47	5.09%	6.647	5.30%	7.521	5.36%	6.653	5.30%	6.92	5.42%
Compressor	87.25	33.01%	51.63	41.10%	55.01	39.23%	51.56	41.10%	52.04	40.79%
Condenser	67.07	25.38	20.42	16.26%	22.3	15.90%	20.42	16.25%	20.63	16.17%
Expansion Valve	38.37	14.52	13.16	10.48%	14.11	10.06%	13.17	10.48%	12.97	10.17%
total Cylcle	264.8	100%	125.6	100%	140.2	100%	125.7	100%	127.6	100%
Exergy destruction reduction	-		52.57%		47.05%		52.53%		51.81%	

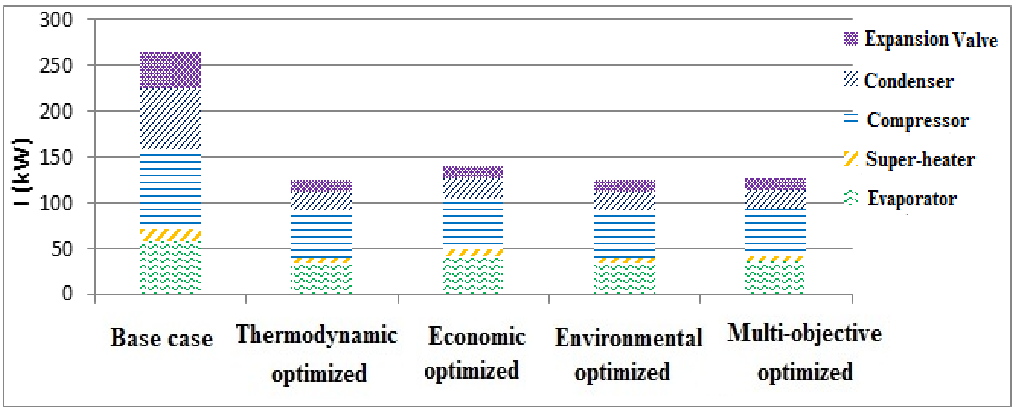

Fig. 3. Comparison of exergy analysis

Table 8. Comparison of the levelized costs including capital investment, maintenance cost, and electricity cost for various designs of the compression refrigeration system

Decision variables	Base case	Thermodynamic optimization	Economic optimization	Environmental optimization	Multi-objective optimization
Capital investment ($/hr)	20.925	33.528	25.4272	32.01	28.9495
Maintenance cost ($/hr)	7.9238	12.7	9.6296	12.124	10.9613
Electricity cost ($/hr)	88.63	46.89	50.14	46.92	47.28
Total cost ($/hr)	117.5	93.13	85.2	91.05	87.19
Total cost improvement (%)	-	20.74%	27.49%	22.51%	25.8%

Figure 5 shows a comparison of the production of environmental pollutants including NOx, CO and CO_2, for various designs of the compression refrigeration system. Fig. 3 indicates that the minimum purchased equipment belongs to the economic optimization system. The multi-objective optimization, environmental optimization, thermodynamic optimization and base case designs are in the next. The minimum electricity cost belongs to the thermodynamic optimization design. This is due to special attention paid to electricity use in the thermodynamic optimization. The environmental optimization, multi-objective optimization, the economic optimization and the base case designs are in the next ranks. Finally, the economic optimization design has the minimum total product cost, $\dot{C}_P$, and the multi-objective optimization, environmental optimization, thermodynamic optimization and base case designs are in the next ranks.

The results shown in Fig. 3, 4 and 5 show that the total product cost, $\dot{C}_P$, is the least in the economic optimization and is the most for the total exergy destruction I_{total}. The thermodynamic optimization design is the best design, and the production of environmental pollutants is the least in environmental optimization. But multi-objective optimization for all purposes has desirable results. It can be said that these deviations from the minimum values in multi-objective optimization design are more acceptable than the other single objective designs.

11.Conclusion

Four scenario optimization of a compression refrigeration system was presented. The proposed method covers thermodynamic, economic and environmental aspects of the system design and component selection.

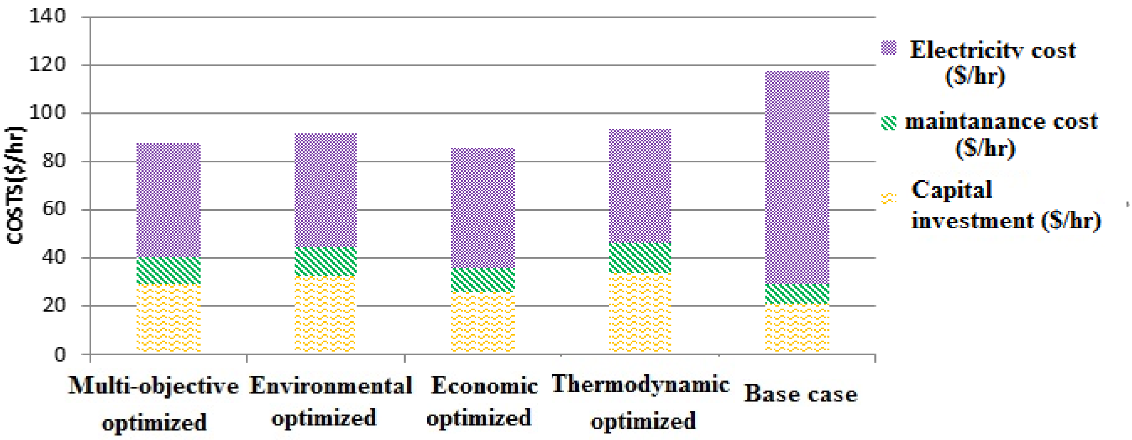

Fig. 4. Comparison of the levelized costs

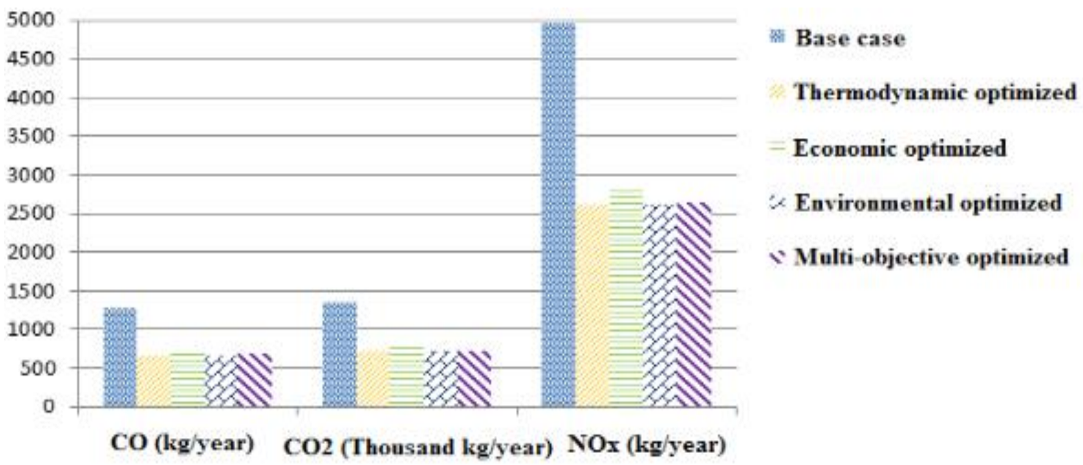

Fig. 5. Comparison of emission product for various designs of the compression refrigeration system

Irreversibility (exergy destruction) for the systems was determined. The economic model of the system was developed, based on the total revenue requirement method (TRR method). The environmental model of the cycle was expressed by the minimization of NOx, CO_2 and CO, which are produced as an effect of power consumption. The configuration of the optimization problem was built with four decision variables and the appropriate feasibility and engineering constraints. The optimization process was carried out by using a multi-objective NSGAII algorithm. Four optimization scenarios including the thermodynamic, economic, environmental and multi-objective optimizations were performed. It was concluded that the multi-objective optimization was a general form of single-objective optimization that considered the three objectives—thermodynamic, economic and environmental—simultaneously. It was discussed that the final solution of the multi-objective optimization depended on the decision-making process. However, its results were somewhere between the corresponding results of thermodynamic, economic, and environmental single-objective optimizations. The thermodynamic optimization was dedicated to the consideration of a limited source of energy, whereas the economic single-objective optimization had concern only for economic resources. The multi-objective optimization focused on limited energy and monetary resources simultaneously. The results show that, ultimately, by comparing the scenarios, multi-objective optimization provides the most comprehensive and best results. It showed that the best results, in comparison to the simple cycle reduction in exergy destruction, by bringing down the figure from 264.8 kW to 127.6 kW (increased coefficient of performance from 3.872 to 7.088), reduction in cold water production cost from 117.5 dollar/hour to 87.19 dollar/hour and reduction in NO_x emission from 4,958 kg/year to 2,645 kg/year.

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