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Economical and Exergical Analysis of Refrigeration Systems

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Abstract: using heat pumps for cooling and heating of buildings is one of the efficient ways of providing required cooling and heating demands with low pollution and cost. In designing the heat pump systems, the reduction of energy consumption for specific heating load is of a great interest. This can not be reached unless the both thermodynamic and economical analysis is being performed for the system. In this paper the equations for the thermo economic analysis of a heat pump system are introduced. This system contains evaporator, condenser, compressor and expansion valve. The mechanical, electrical and isentropic efficiencies of compressor, also the cycle superheating and sub cooling degrees are considered. For such a system an objective function which is some of the capital and operational costs is introduced. By applying the numerical search method as an optimization technique, the system design parameters are obtained. The objective function for these optimum design parameters is minimized. The system exergy analyses at the optimum design point show that the system exergy destruction was also reduced. For optimization of the objective function, the GAMS software was used. In some references exergy analyses and in other references economical analyses on thermodynamics systems have. In this paper both thermodynamics and economical analyses have been worked and there is a comparison with some references that reduction of exergy losses in noticeable here.

Key words: Heat pump · Exergy and thermoeconomic

INTRODUCTION

“Heat-pump” is a machine that transfers heat from place to place by carrying out work. The technology in most of the heat-pumps is the transfer of heat from a low temperature to a heat-well with high temperature.

Heat-pump is a kind of refrigeration machine that uses voided heat of condenser for heating the building. It is done by expending work in compressor and taking heat from a source with low temperature and transferring it to a source with high temperature.

The design of heat-pump should make possible the use of voided heat of condenser for heating the building. At the same time, this system uses the produced frigidity produced from evaporator to cool the building.

The head-pump is popular and suitable for heating and cooling the building. These systems are more effective than traditional combustion systems or electrical short circuit technologies. They are suitable and commodious, especially in regions that have rough winters. So, the heat-pump systems have suitable and usual fuel and electricity expenditure.

Thermoeconomic Optimizaition: The thermoeconomic method has been used for designing and optimizing the heat-pump system. This is a suitable method for the present in using thermodynamic processes and amount of exergy loss.

We can obtain information about ability or capacity of improving the function of the processes of a system by using thermodynamically analysis in designing and optimizing a heat-pump system [1].

However, by applying technical economical analysis, in addition to survey of function of processes improvement, it is specified that to what extent improvement in function of processes is commodious. Also, by using thermo economic analysis, we can specify marginal cost of arbitrary variable and independent parameters like efficiency of compressor, evaporator, condenser and electric motor, which are chosen variables and should be optimized and obtained.

The results show that the electric motor is the critical component of system and is very important and also the most exergy lose reduction happens in electric motor.

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The objective function Φ0 is defined as a function of state parameters {xj}, where {xj} is abbreviation for x1, x2,...xj...xn, decision variables {yk} and decision parameters {zl}, i.e. [1].

$$\Phi 0 = \Phi 0 (\{xj\},\{yk\},\{zl\}),$$

Where j=1,2,..., n, k=1,2,..., m and l=1,2,..., r.
The equations of state are

$$\Phi j (\{xi\},\{yk\},\{zl\}) = 0, j = 1,2,..., n.$$

The optimization is formulated as follows:

$$\text{Minimize } \Phi 0 = \Phi 0 (\{xj\},\{yk\},\{zl\}),$$

$$\text{Subject to } \Phi j (\{xi\},\{yk\},\{zl\}) = 0, j = 1,2,..., n.$$

The exergy losses due to irreversibility's in a stationary state is determined for each component by regarding in and outflows of exergy. The exergy content is:

$$E = H - T0S - \Sigma \mu c0\ nc.$$

For the system, we obtain a sum for all components, which gives the total rate of exergy loss. This may also be written the product of the reference temperature and total entropy production, i.e., T_0 Δstot.

Heat-pump System and Thermoeconomic Analyses: Heat-pump system, which is shown in Figure below [2] and its temperature-entropy diagram, is used for thermodynamic analysis and exergy computation. This system, by considering isentropic efficiency, electrical and mechanical efficiency of compressor and by bringing into account that exiting gas from evaporator becomes superheated and exiting saturated refrigerant liquid from condenser becomes super cooled, has approached to qualification of a real cycle [3].

By the help of thermoeconomic method, we can calculate objective function and determine preliminary investment cost for each component, which is according to time. The sum of cost according to time, i.e., an objective function, is the sum of these costs and cost of consumed electricity in the same period of time, which is defined as below: [4, 5].

$$\phi_o = \sum_{i=1}^{5} c_i + tP_{e1}E_{e1}(\$/yr)$$

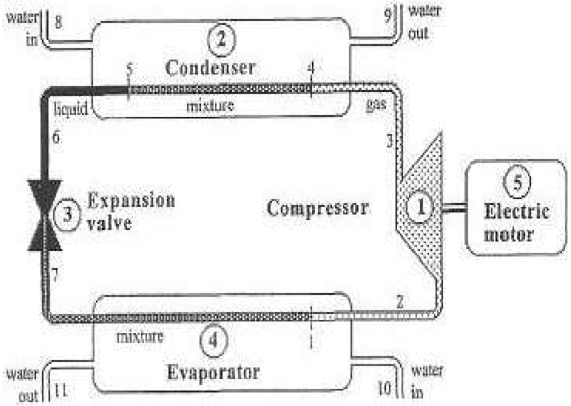

Fig. 1: Schematic diagram of heat-pump system

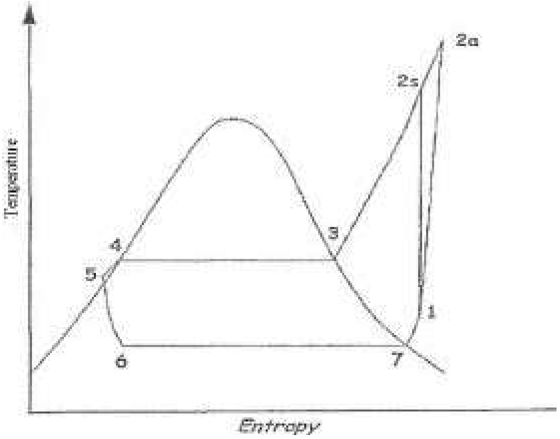

Fig. 2: Temperature-Entropy Diagram of heat-pump cycle

Elsayed and Tribos [6, 7] have expanded the concept of thermo economic and showed that the objective function has been optimized and has economical and technical limitations and thermo economic means that by introducing methods as proposal and simultaneous improvement, some analyses of system can be improved.

For optimizing system, a preliminary system with assumed characteristics should be presented so that, by the help of the present methods, can carry out optimization on independent parameters, because independent parameters are necessary for calculating the preliminary costs of system and are used in calculating objective function.

When this method is used, the difference between all in coming exergy flows and all out going exergy lows must be minimized and the efficiency must be maximized.

Calculating the amount of optimized efficiency for system will lead to diminution of objective function and this means commodiousness.

The Concept of Optimization: Optimizing a process is finding qualifications in which maximum and minimum of a function is acquired. Optimization is a principle in engineering.

For optimizing a system, the parameter which is to optimized should be calculated, as objective function in terms of design variables. (System assimilation).

In general, two major methods are applied for optimization:

Search Method

Special Purpose Method: In optimizing heat cycles, we can't use methods which require function of system so that by differentiation preliminary function, can optimized amounts are acquired. Because in these systems, objective function in this optimization isn’t a simple and peculiar relation so that be differentiated easily. The methods are used in optimizing heat cycles which don’t require derivative of objective function [8].

Some of these methods are:

Nelder, Meed, Hooke, Jeeves, Rosenbrock, Univariate, Full search.

Full search method is on of the first multivariable methods for finding optimized spot. This method has a simple and exact structure. The base of this method is perusing all the spots around the beginning point, finding the best point and moving toward it. There are three statuses for each variable in this method: moving a step forward, moving a step backward, or maintaining the position. So, the number of spots which should be checked for each stage equals to 3n. n, represents the number of variant parameters of system and here it is 4.

There are different soft wares for optimizing objective function. One of the software's which are used for optimizing objective function by Full search method is GMAS, which is used in this paper.

Analysis of Heat-pump Optimization: The preliminary costs of investment for any system components are as below: [4, 5].

Compressor: $C_1 = a_1 k_1 \frac{V_1}{0.9 - \eta_1} \frac{p_2}{p_1} \ln \frac{p_2}{p_1}$

Condenser: $C_2 = a_2 k_2 m_{wh} \sqrt{\frac{\eta_2}{1-\eta_2}} = a_2 k_2 m_{wh} \sqrt{e^{NTU_2} - 1}$

Expansion Valve: $C_3 = a_3 k_3 m_r$

Electric Motor: $c_5 = a_5 k_5 p \frac{\eta_5}{1-\eta_5}$

η1, η2, η4 and η5 are defined as below:

Efficiency of compressor: $\eta_1 = \frac{h_{2s} - h_1}{h_2 - h_1}$

Efficiency of condenser: $\eta_2 = \frac{T_9 - T_8}{T_4 - T_8}$

Efficiency of evaporator: $\eta_4 = \frac{T_{11} - T_{10}}{T_1 - T_{10}}$

Efficiency of electric motor: $\eta_5 = \frac{m_r (h_2 - h_1)}{p}$

Furthermore, the annuity factors of the different capital investment are defined as below [4, 5]:

$$a_i = \frac{r}{1 - (1+r)^{-ni}}$$

The depreciation time ni may vary for each component due to variation in economic lifetime and maintenance costs such as renovations, etc [9].

Figure 3 shows the investment costs as a function of the efficiencies. A typical “knee”, from the “penalty function”, can be observed for the compressor and the electric motor at specific values of the efficiencies, approximately at 86 and 94% respectively. if the compressor and the electric motor are regarded as given, or limited to a number of possibilities, the decision space is limited to one, or a number of, two dimensional rooms, defined by the efficiencies of the condenser and the evaporator, i.e., the only two decision variables [10].

RESULTS

The amounts of compressor, condenser, evaporator and electric motor efficiencies for a vapor-compression refrigeration system which uses R-134a refrigerant are 0.75, 0.75, 0.75 and 0.78 respectively [9].

After optimizing the objective function, these amounts are calculated for independent variables of system:

η1 = 0.8, η2 = 0.84, η4 = 0.8 and η5 = 0.9

The cycle is designed by applying η1, η2, η4 and η5.

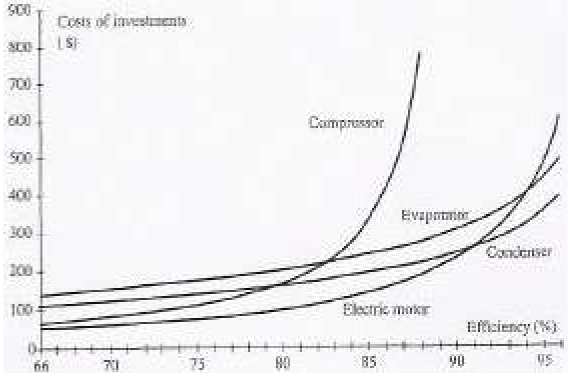

Fig. 3: Costs of investments as a function of the efficiencies.

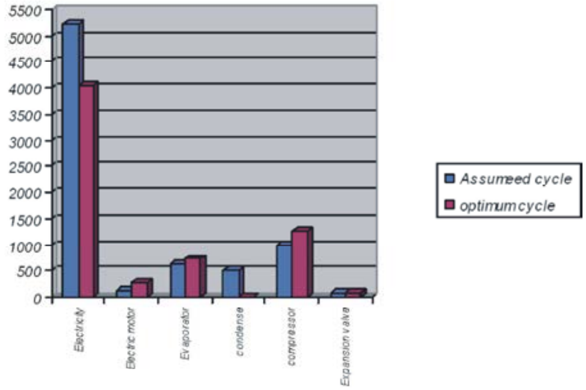

Fig. 4: Costs for the assumed and the optimum system

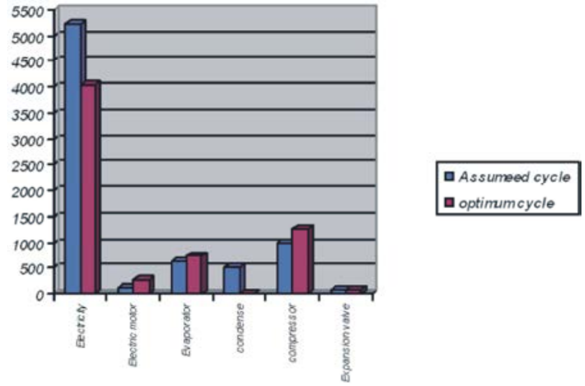

Fig. 5: Energy losses for the assumed and the optimum system.

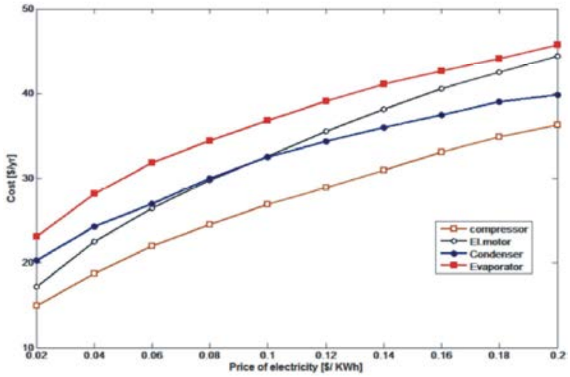

Fig. 6: Component costs as a function of the price of electricity when output heat is 50°C

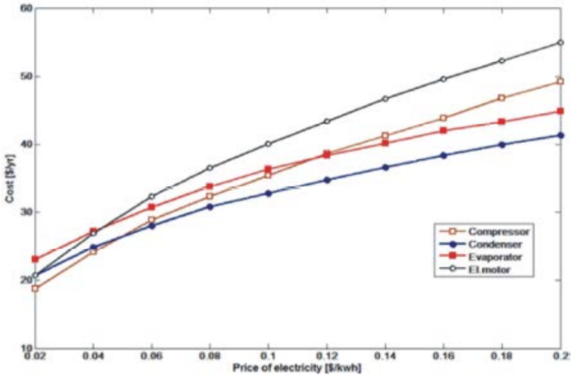

Fig. 7: Component costs as a function of the price of electricity when output heat is 60°C.

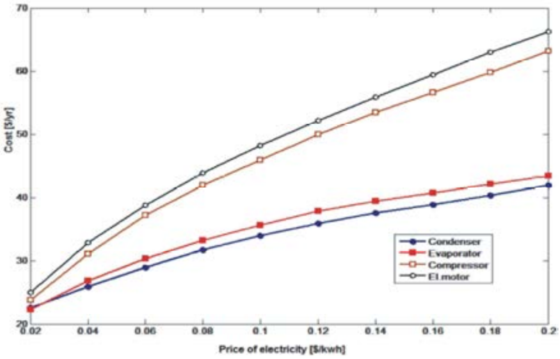

Fig. 8: Component costs as a function of the price of electricity when output heat is 70°C.

For the assumed system, the sum of preliminary costs is 7566.46$/year. 5220$/year is for electricity. When optimized amount are brought into account, the sum of preliminary investment becomes 7007.93$/year from which 4040$/year is for electricity [11]. After optimization, it is clarified that the sum of optimized system, in comparison to assumed system, has decreased 558.53$/year, that is, 7.38%.

The comparison between preliminary costs for assumed system and optimized system for each component are shown as below:

The sum of exergy loses, in comparison between assumed system and optimized system, has been decreased from 122.77kw to 98.26kw. the differences of exergy loses has been shown as below:

The expansion valve accounts for a larger fraction of the total exergy loss in the optimum system, which further justifies investment in research and development to improve it.

When the exergy loss in assumed system and optimized system is compared, it is seen that the most exergy loss decrease has happened in electric motor. This component in optimized status has 12.99kw decrease in exergy loss, in comparison to primitive status. it shows that electric motor is the most important component in assumed cycle and optimization of this component has the main role in decreasing more exergy loss. Coefficient of performance (cop) has increased from 1.12 in assumed system to 1.84 in optimized system.

In order to further show the usefulness of the method, the dependence on or sensitivity to the cost of electricity and the temperature of the produced heat (T9) has also been studied.

Figures 6, 7 and 8 show a proportion between the costs of each component and the price of electricity. By using these diagrams we can compare the sum of costs when temperatures are 50°C, 60°C and 70°C and reach to ideal results. For example, when the temperature is 50°C, the costs at 2 \$/kwh increases from 2296\$/year to 13891\$/year. If the optimum at 0.2 \$/kwh [12] had been used at 2 \$/kwh, thenthetotal cost would be 15913 \$/year, i.e., an increase in the cost of 2022 \$/year.

We can understand from figures 6, 7 and 8 that when the price of electricity is high, high price of components will be effective.

This might have been anticipated, but the exact interrelations could not have been foreseen.

When the increase in total cost of each component and outputs is seen, it can be concluded that choosing evaporator has less cost and is more commodious.

The results acquired in this paper may be acquired by other methods and computer programs. The results of different systems and refrigerants may be different.

The aim of this part is to show that by applying thermo economic method, we can acquire useful results for refrigeration systems which can decrease the costs. Of course numerical analysis is required to acquire these results.

Nomenclature:

a	Annuity factor, dimensionless
c	Cost per unit time,\$/yr
E	Exergy, j
Eel	Electricity used per year, j/yr
h	Specific enthalpy, j/kg
H	Enthalpy, j
k	Constant factor
m	Mass flow, kg/s
NTU	Number of heat transfer units, dimensionless
nc	Quantity of substance *c,* kg
ni	Depreciation time for component *i*, yr
r	Interest rate, dimensionless
T	Temperature, k
T0	Reference temperature, k
t	Operating time per unit time, dimensionless
s	Entropy, j/k
v	Volume, m^3
x	State parameters
y	Optimization or decision variable
z	Decision parameters
Δstot	Total entropy production, j/k
Φj	Equations of state
Φ0	Objective function, \$/yr
η	Efficiency, dimensionless
μ	Chemical potential, j/kg

Subscripts:

c	Substance
el	Electricity
I	Component
r	Refrigerant
wc	Water on cold side
wh	Water on hot side
0	Reference state

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