ELEMENTS OF EXERGOECONOMICS FOR THE ANALYSIS OF COMPRESSOR HEAT PUMPS

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Abstract

Methods of modern applied thermodynamics, such as exergy analysis, method of minimization entropy generation, thermoeconomics (exergoeconomics) is becoming a standard practice for optimizing energy conversion systems and their elements. Naturally, these methods should find wide application for the analysis and optimization of heat pumps. In the paper author discuss basic moments of application of exergoeconomics for the analysis of compressor heat pumps: advance calculation of physical exergy and exergoeconomic model are given.

KEYWORDS

Heat pump, exergy analysis, exergoeconomic analysis.

INTRODUCTION

Exergy analysis expands spheres of rational application in problems of the analysis and optimization of energy conversion and chemical-technological systems. There were more that 2 million scientific publications during last 10 years where concepts of exergy analysis are applied.

Problems of connection of thermodynamic and economic calculations take attention of specialists for a long time. Exergoeconomics as the modern direction of applied thermodynamics is connection of the Second Law of thermodynamics and the theory of cost. For today exergoeconomic method of the analysis and optimization represents the powerful tool for scientists and the engineer-designers [1].

Development of exergoeconomic theory goes by the way of perfection of methods for cost definition of a working fluid flow between elements of an energy conversion system. In basic elements of energy conversion systems (compressors, pumps, turbines, heat exchangers etc.) physical exergy of working fluid flow is changing only. Thus in problems of exergoeconomic analysis and optimization the main role creation of the theory and engineering methodic of splitting physical exergy into its thermal and mechanical components is played. After it, definition of cost of each components of physical exergy is necessary. Such approach creates preconditions to more correct optimization by exergoeconomic methods.

Let us consider the new approach for creation of exergoeconomic model of a vapor-compression heat pump.

EXERGOECONOMIC MODEL

Exergy cost is one of main principles of exergoeconomics which note, exergy more important that energy or mass of working fluid flow should be examined for definition of cost of energy transformation in an energy conversion system.

The cost per exergy can be was earlier determined by following approaches:

- as *limiting* (minimal or maximal) *cost*. It was first method proposed by M.Tribus, R.Evans and Y.El-Sayed, for example [2, 3];
- as *average cost*. This approach is used in exergoeconomic methods developed as alternative method, for example, [4-6];
- by *specific exergy costing* method (SPECO-method). This method is modern and proposed in [7]. Author use SPECO-method for this paper.

Exergoeconomic balance is general equation for the analysis by the SPECO-method

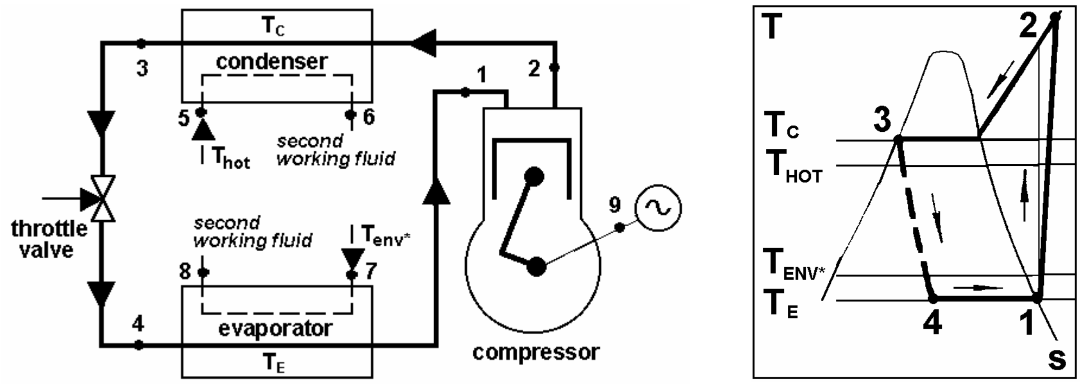
$$\underbrace{C_{q,k} + \sum_i C_{i,k} + Z_k}_{\textit{inlet cost}} = \underbrace{\sum_e C_{e,k} + C_{w,k}}_{\textit{outlet cost}} . \tag{1}$$

Cost of any working fluid flow can be determined by multiple of specific exergy cost value (c_k) and exergy of flow (E_k) value as

$$C_k = c_k E_k \tag{2}$$

Physical exergy is basis of exergoeconomic model

Schematic solution of simple vapor compression heat pump and corresponding thermodynamic cycle (by Plank cycle [8]) are shown in Fig.1.



a) b)

Fig.1. Vapor-compression heat pump: a) simple schematic solution; b) cycle in the diagram *T-s*

Full exergoeconomic model of the vapor compression heat pump can be represents by four equations

$$\left.\begin{aligned} \dot{C}_1 + \dot{C}_9 + Z_{CM} &= \dot{C}_2, \\ \dot{C}_2 + \dot{C}_5 + Z_C &= \dot{C}_3 + \dot{C}_6, \\ \dot{C}_3 + Z_{TV} &= \dot{C}_4, \\ \dot{C}_4 + \dot{C}_7 + Z_{EV} &= \dot{C}_1 + \dot{C}_8. \end{aligned}\right\} \tag{3}$$

There are 13 variables in the system of eq. (3). Probably, solution of this system should not represent the big problems because of values Z_{CM}, Z_C, Z_{TV}, Z_{EV} and $\dot{C}_9$ can be accepted as known. Thus it is necessary to write 4 equations more or to determine anyone 4 variables from $\dot{C}_1 ... \dot{C}_8$ trough connect among themselves.

Let us analyze of opportunity to 'break off' of the heat pump cycle by exergoeconomic analysis point of view, i.e. to appoint exergy cost of one of 8 flows ($\dot{C}_1 ... \dot{C}_8$). Usually, value of C_j can not be determined prior to the analysis. Except case is when C_j is electric energy (for example, flow C_9 on Fig. 1). It is much easier to consider an opportunity of *assignment* value C_j=0.

(A) For example, $\dot{C}_4 = 0$. This assumption can be accepted for heat pump, for example in work [9]. Cycle of heat pump was 'braked off' and exergoeconomic analysis was carried out by using one equation for definition increasing (decreasing) values of exergy cost of working fluid flow through each element

$$\Delta c_k = \frac{Z_k + c_{p,k} E_{D,k}}{E_{F,k}} = \frac{Z_k + c_{F,k} E_{D,k}}{E_{P,k}} . \qquad (4)$$

Of course, definitions of exergies of 'product' and 'fuel' must be determined, for example by [1, 6, 7].

The assumption $\dot{C}_4 = 0$ is absolutely impossible if the level of 'cold production' of heat pump is below or above environmental temperature ('zero' level from exergy point of view).

(B) For example, $\dot{C}_1 = 0$. This assumption can be accepted for heat pump analysis at presence of some auxiliaries elements and certain temperatures as operating conditions.

(C) For example, $\dot{C}_2 = 0$. This assumption can not be accepted for heat pump. There is supply of 'primary energy' ('fuel' of heat pump) by the compressor to all heat pump. For the heat pump the flow $\dot{C}_2$ is the most expensive.

(D) Example $\dot{C}_3 = 0$ is similar to $\dot{C}_1 = 0$.

By definition of exergy it is availability energy by presence of a difference of temperatures ($T \neq T_O$) and pressure ($p \neq p_O$) between working fluid flow (T, p) and environmental ones (T_O, p_O). Thus each flow from $\dot{C}_1 ... \dot{C}_8$ is necessary to split into thermal and mechanical components. Probably definition of $\dot{C}_k^T$ or $\dot{C}_k^M$ will be more easy.

Components of physical exergy are basis of exergoeconomic model

Let us consider once again an opportunity to assignment exergy cost of working fluid flow taking into account splitting physical exergy into its thermal and mechanical components.

Cost of $\dot{C}_4 > 0$ is determined unequivocally by cost of $\dot{C}_4^T > 0$ because cost of $\dot{C}_4^M = ?$ and will be determined by value of p_4 and more correct by pressure difference ($p_4 - p_O$).

Cost of $\dot{C}_1 = ?$ is determined by cost of $\dot{C}_1^T$ ($\dot{C}_4^T = 0$ if $T_1 = T_{env}$) and low cost of $\dot{C}_1^M$ because of $p_4 \neq p_O$ but $p_4 < p_2$.

High cost of $\dot{C}_2$ is determined by high cost of $\dot{C}_2^T$ and $\dot{C}_2^M$ simultaneously.

Cost of $\dot{C}_3$ will be determined by high cost of $\dot{C}_3^T$ (but $\dot{C}_3^T < \dot{C}_2^T$) and high cost of $\dot{C}_3^M$ ($\dot{C}_3^M = \dot{C}_2^M$).

All explanations testified that exergoeconomic model creation of vapor-compression heat pump needs obligatory division of splitting physical exergy into its thermal and mechanical components.

Let us rewrite system of eq.(3), taking into account splitting physical exergy of each working fluid flow into its thermal and mechanical components.

Equation 1. Exergoeconomic balance for compressor is

$$\dot{C}_1^T + \dot{C}_1^M + \dot{C}_9 + Z_{CM} = \dot{C}_2^T + \dot{C}_2^M . \qquad (5)$$

Equation 2. For compressor (by [7])

$$\frac{\dot{C}_2^T + \dot{C}_1^T}{\dot{E}_2^T + \dot{E}_1^T} = \frac{\dot{C}_2^M + \dot{C}_1^M}{\dot{E}_2^M + \dot{E}_1^M} . \qquad (6)$$

Equation 3. Exergoeconomic balance for condenser is

$$\dot{C}_2^T + \dot{C}_2^M + \dot{C}_5^T + \dot{C}_5^M + Z_C = \dot{C}_3^T + \dot{C}_3^M + \dot{C}_6^T + \dot{C}_6^M . \qquad (7)$$

For a heat exchanger or condenser as example (by [7])

Equation 4. $c_5^T = known$,

Equation 5. $c_5^M = known$,

Equation 6. $c_6^M = c_5^M$,

Equation 7. $c_3^M = c_2^M$,

Equation 8. $c_3^T = c_2^T$,

Equation 9. Exergoeconomic balance for throttle valve is

$$\dot{C}_3^T + \dot{C}_3^M + Z_{TV} = \dot{C}_4^T + \dot{C}_4^M . \qquad (8)$$

Equation 10. For expansion process as throttling

$$c_4^M = c_3^M .$$

Equation 11. Exergoeconomic balance for evaporator is

$$\dot{C}_7^T + \dot{C}_7^M + \dot{C}_4^T + \dot{C}_4^M + Z_{EV} = \dot{C}_1^T + \dot{C}_1^M + \dot{C}_8^T + \dot{C}_8^M . \qquad (9)$$

For a heat exchanger or evaporator as example (by [7])

Equation 12. $c_7^M = known$,

Equation 13. $c_8^M = known$,

Equation 14. $c_1^M = c_4^M$,

Equation 15. $c_1^T = c_4^T$,

Equation 16. $c_7^T = known$,

Equation 17. $c_9 = known$.

Thus we have full exergoeconomic model by 17 equations. Cost of 'product' of heat pump is cost of product of condenser

$$\dot{C}_{P,tot} = \dot{C}_6 - \dot{C}_5 = \left(\dot{C}_6^T - \dot{C}_5^T\right) + \left(\dot{C}_6^M - \dot{C}_5^M\right). \qquad (10)$$

PHYSICAL EXERGY SPLITTING

Principles of using thermal and mechanical components of physical exergy in problems of exergoeconomic analysis and optimization have been developed earlier (for example, in [7]). Their practical application can be possible only after creation of the theory of splitting physical exergy. Many authors have made attempt of splitting physical exergy into thermal and mechanical components, for example in [10-13] but their theoretical researches had no calculation confirmations and was not accepted for practical application.

The proposed engineering methodic of physical exergy splitting was confirmed by 4 models: two theoretical ones by use of higher mathematics principles [14,15] and by two graphic ones [16] and, therefore, can be recognized as correct

$$e^{PH} = (h - h_O) - T_O(s - s_O) \tag{11a}$$

or

$$e^{PH} = \underbrace{(h - h^*) - T_O(s - s^*)}_{e^T} + \underbrace{T_O(s_O - s^*) - (h_O - h^*)_{T_O=const}}_{e^M} . \tag{11b}$$

On the basis of eq. (11b) which can be used in engineering practice, it is necessary to have the following data for calculation thermal and mechanical exergy for any point:

- thermodynamic parameters of working fluid in a considered point with coordinates (p, T, h, s);
- thermodynamic parameters of working fluid in the point 'O' with coordinates (p_O, T_O, h_O, s_O);
- values of enthalpy (h^*) and entropy (s^*) in the auxiliary point '*' at $p^* = p$ but $T^*=T_O$.

CALCULATION DATA

Let us consider vapor-compression heat pump that is working with solar collector system (Fig.2).

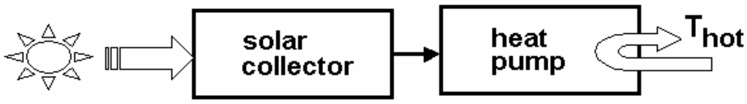


Fig.2. Heap pump system with solar collector

Giving data for thermodynamic model (exergy analysis) are: T_{hot} = 120 °C ; T^*_{env} (from solar collector) = 80 °C; heat production is Q_C=3 MW; T_{env} = 25 °C (for exergy analysis).

Following values have been chosen as average from numerous experience of designing and operation: adiabatic efficiency of the compressor η = 0,85; temperature difference in the condenser and the evaporator is ΔT = 10°.

The condenser and the evaporator is pipes type heat exchanger, type of compressor is piston compressor.

Choice of working fluid for high temperature heat pump is very important and difficult (this question is not consider in the present work). In basis of previously works, author propos water (R718) as working fluid [17].

Giving data for economic model are: specific cost of exergy 'fuel' (c_F) for the compressor, and, hence, for all heat pump is the price for the electric power (3,48 × 10^{-2} Euro/(kW·h)).

Capital cost of each element of heat pump can be determines as [9,17]

$$Z_k= a_k\, x_k^{\,n}(1+b)^y/N_k, \tag{12}$$

where x is value of main parameter of a component; a is cost of unit of equipment; n,y are coefficients; N is maximal operational period, year (Table 1).

Table 1. Data for economic model

Element	Parameter of the equipment *(x)*	Specific cost *(a)*	*n*	*b*	*y*	*N*
Solar collector	Heat exchange surface is 21206 m^2	13 Euro/m^2	1	0,06	4	20
Compressor	Consumed power 587 kW	292 Euro/kW	0,95	0,06	2	10
Condenser	Heat exchange surface is 129,2 m^2	13 Euro/m^2	0,6	0,06	2	15
Evaporator	Heat exchange surface is 102,9 m^2	74 Euro/m^2	0,53	0,06	16	15

Exergy model

Thermodynamic properties of point 1, 2, 3 and 4 of thermodynamic cycle of heat pump (Fig.1b) and corresponding thermodynamic properties of points 'O', point '*' for pressure p_2=p_3 and point '*' for pressure p_1=p_4 in Table 2 are present.

Calculation data of exergy analysis in Table 3 is present.

Table 2. Data for exergy analysis

Property	Unit	Points						
		1	2	3	4	‘O’	‘*’ for $p_2=p_3$	‘*’ for $p_1=p_4$
Pressure	p, MPa	0.0315	0.273	0.273	0.0315	0.1	0.273	0.0315
Temperature	T, °C	70	338	130	70	25	25	25
Enthalpy	h, kJ/kg	2618	3143	550	550	108	108	108
Entropy	h, kJ/kg grad	7.725	7.869	1.644	1.704	0.378	0.317	0.378

Table 3: Calculation data of exergy analysis

Specific exergy, kJ/kg	Points			
	1	2	3	4
e^{PH} by eq.(11a)	320.53	802.62	64.67	46,78
e^{T} by eq.(11b)	320.60	802.39	64.44	46,85
e^{M} by eq.(11b)	-0.07	0.23	0.23	-0.07

From Table 3 is visible that for giving operation conditions of heat pump with water as working fluid thermal components of physical exergy in each point of cycle are bigger values that mechanical one.

Exergoeconomic model

Exergoeconomic model of heat pump in Fig. 3 is present. Throttling process was not included in the analysis. Value $C_{D,k} = c_k E_{D,k}$ where exergy destruction was determined by Guy-Stodola theorem as

$$E_{D,k} = T_O S_{gen,k} \quad . \tag{13}$$

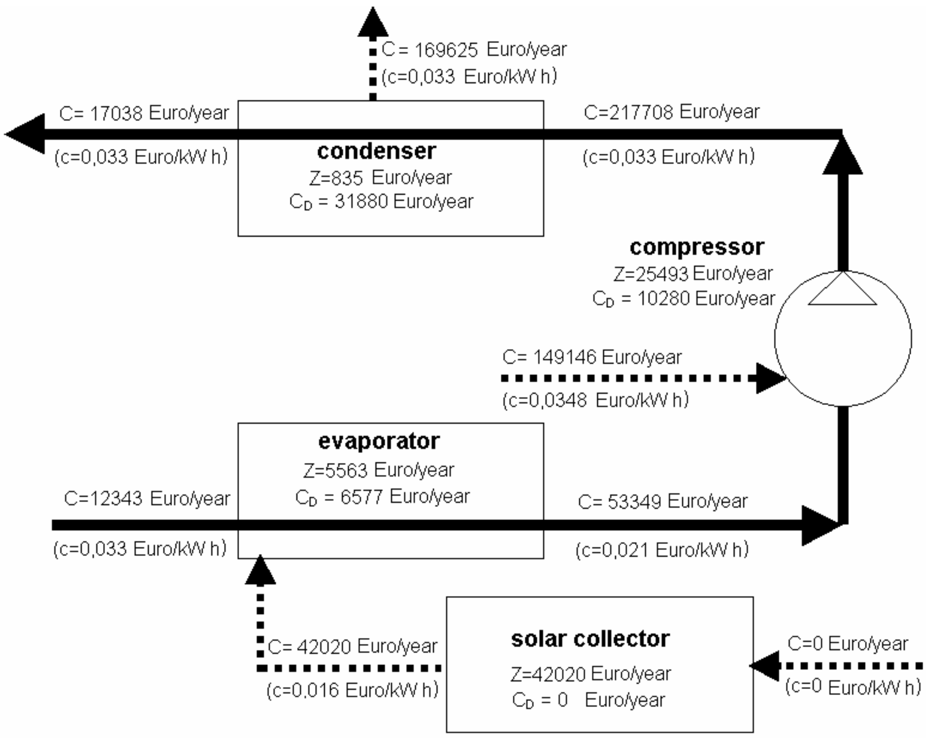


Fig. 3. Exergoeconomic model of heat pump

CONCLUSION

The paper discusses novel approaches to the heat pump analysis with widely using exergy and exergoeconomic concepts. In the first time present exergy model and full exergoeconomic model of vapor-compression heat pump by splitting physical exergy into its thermal and mechanical components.

The author's proposition for calculating the thermal and mechanical components of physical exergy can be used in engineering calculations for analysis and optimization purposes.

ACKNOWLEDGEMENTS

Prof. T. Morosuk grateful acknowledges the support by Alexander von Humboldt Stiftung (IV-UKR/1117838) which enables her scientific work at the Institute for Energy Engineering, Technical University of Berlin.

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