ijates
ISSN 2348 - 7550

EXERGY COST ANALYSIS OF VAPOUR ABSORPTION REFRIGERATION SYSTEM (VARS) BASED ON THERMOECONOMIC MODEL.

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ABSTRACT

This article presents *exergy cost analysis* of a single stage vapor absorption refrigerant system (VARS) with water-LiBr pair whose energy source is waste steam. The aim of Exergy Cost Analysis is to define the cost formation process of products and residues in the operation of energy conversion systems. In the first part of this work, authors have described a thermoeconomic data model to obtain the Fuel-Product table for the above VARS. This model is a fundamental concept of symbolic exergoeconomics. The FP table represents the productive structure which shows, where the product of each component is used and the origin of the resources of each component. In the later part of this article, complete exergy cost analysis is performed by applying FP table as input data. This approach allows one to find the exergy cost of each subsystem of the proposed vapor absorption refrigerant system. Besides, the unit exergy cost of the product is decomposed in the contributions of the irreversibilities of each subsystem and the contribution of each residue.

Keywords: Exergoeconomics; thermoeconomic modeling; exergy cost analysis; vapour absorption refrigeration

I. INTRODUCTION

Vapour Absorption Refrigeration Systems (VARS) are alternative to vapour compression refrigeration systems. However, unlike vapor compression refrigeration systems, the required input to absorption systems is in the form of heat. These systems are preferred when low-grade energy such as waste heat or solar energy is available. Since conventional absorption systems use natural refrigerants such as water or ammonia, they are environment friendly as they eliminate the use of CFC and HCFC refrigerants. Moreover, these systems present other advantages, such as high reliability, low maintainability and silent and vibration-free operation [1]. Vapour absorption refrigeration systems (VARS) using water-lithium bromide pair are extensively used in large capacity air conditioning systems. In these systems water is used as refrigerant and a solution of lithium bromide in water is used as absorbent. Single effect absorption refrigeration systems have only one heating level of the working fluid (dilute solution). The Coefficient of Performance (COP) of these systems, working with a LiBr/H2O solution, is in the range of 0.6 to 0.7. [2].

Thermoeconomics [3-6] is a combination of thermodynamics and economics, used as an exergy aided cost reduction method to support the design and operation of energy systems with maximum efficiency. In the first step, thermoeconomic modeling of proposed VARS is presented on the basis of thermoeconomics Input-Output analysis [7]. To define the complete productive structure, one or several fuel and product streams as the collection of the flows that constitute them, for every component of system, are identified [8]. This model is also called the Fuel–Product model and can be represented mathematically by means of Fuel Product table [9].Torres demonstrated the capability of thermoeconomic modeling by means of a case study based on the integration of a power plant, a cement klin and a gas fired boiler [10]. He presented a detailed thermoeconomic model for a simple combined cycle, which defines the productive purpose and the distribution of resources and internal products of the entire system using physical model as reference [11].

exergy cost analysis of energy conversion system is one of the most important applications of thermoeconomic model [12]. The objective of exergy cost analysis is to detect inefficient components of an energy system, by quantifing the impact of each one of them in terms unit exergy cost of the product [13]. Torres, Valero and Perez have presented complete exergy cost analysis for a gas turbine cogeneration plant including irreversibilities, the thermoeconomic cost for the entire cogeneration plant [14]. In the proposed analysis, the exergy cost of the each components of the VARS using water-lithium bromide pair, including the effect of the irreversibilities of the components involved in the production process and the residues are described. The complete exergy cost analysis is performed by using the software TAESS (Thermoeconomic Analysis of Energy Systems Software. TAESS is developed in CIRCE (Center of Research for Energy Resources and Consumption) and the Department of Mechanical Engineering of the University of Zaragoza (Spain), to execute the thermoeconomic analysis of energy systems from their thermodynamic model and productive structure.

II. FORMULATION OF THERMOECONOMIC MODEL

To perform a *exergy cost analysis* of an energy system, it is required to formulate a thermoeconomic model, which defines the productive purpose, to define the efficiency of each component of the system, as well as the distribution of the resources and internal products through the entire energy system, using the physical model as reference. The input data for performing the thermoeconomic modeling are the exergy of each flow of the system; those are obtained from the result of computer simulation for Thermodynamic analysis of the single stage water-LiBr system.

2.1 Physical Structure

The diagram of the physical structure of the proposed VARS is shown in the figure 1. The definition of physical structure consists of indicating the pair of components that each flow of the systems connects. Each flow of the VARS system leaves from a component and enters to another component. The environment is considered as the device “0”. In this modeling, an important assumption, as explained by Misra, Sahoo & Gupta (2002), has been made of coupling the expansion valves and pressure reducing valves to their corresponding control volume equipments that immediately followed them [15]. This is due to the irreversible nature of the valves and these devices have the effect of destruction of exergy. Refrigerant valve (ER) will be the part of evaporator and solution valve (ES) will be the part of absorber.

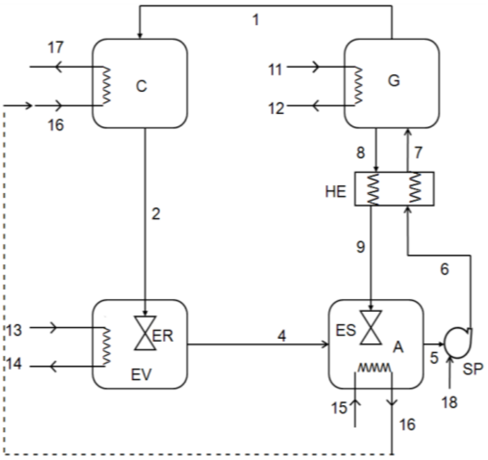

Figure 1. Representation of single stage water/LiBr VARS for thermoeconomic modeling.

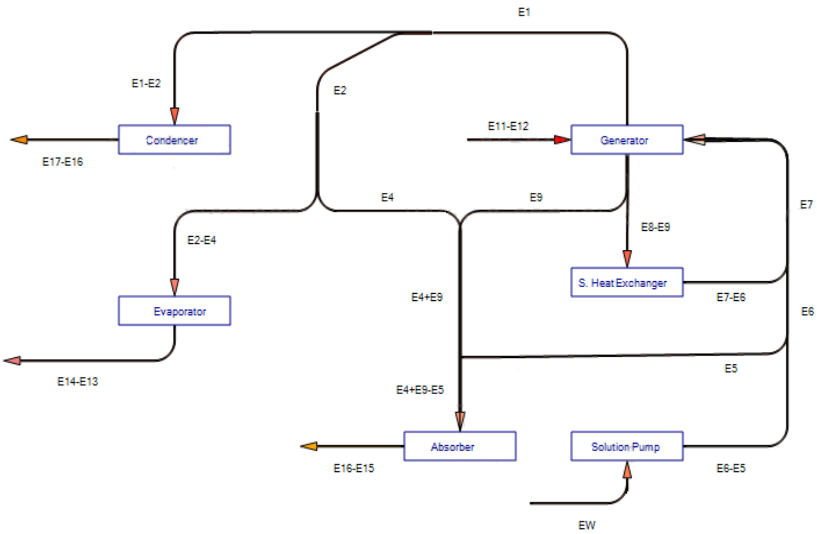

Figure 2. Graphical representation of productive structure of single stage water/LiBr VARS.

2.2 PRODUCTIVE STRUCTURE

Each component or process of the system has a productive purpose. It is recognized by means of the definition of its efficiency:

Efficiency = Product/Resources

For each process or component of the system is necessary to define the flow streams that constitute its product streams, and the flow streams used to obtain them, called fuel streams. Accordingly, the fuel is the amount of exergy provided by the fuel streams, and the product is the exergy provided by the product streams. The Environment extends everything outside the limits of the system (control volume). The resources of the environment are all the system outputs and its products are all the system inputs. Figure 2 shows the graphical representation of the complete productive structure of the whole VAR system analyzed in the paper which represents the *fuel* and *product* definition of each component of the system

2.3 GENERAL DATA FOR TAESS ANALYSIS

Authors have modeled the Vapour Absorption Refrigeration Systems in TAESS (software tool) with the results from thermodynamic analysis to obtain the results of the *exergy cost analysis*. This approach requires to have exergy of each flow of the system.

To completely define the system configuration one should know the number of flows, the number of productive devices and the number of dissipative devices. The purpose of productive devices is to provide resources to other components or to obtain the final product of the system. Purpose of dissipative devices is to reduce or eliminate the environmental impact of the residues generated in other devices. Their usefulness lies in interacting with other components to allow improved system efficiency. In the present example of VARS, the condenser and the absorber are dissipative devices and their objective is to expel the heat of condensation and the heat of absorption respectively to the environment. Hence, there are six devices (4 productive and 2 dissipative) and sixteen flows for our system. Table 1 represents the definition of device configuration in TAESS which contains the number, name and type of various components of proposed VARS system.

Table 1. TAESS device configuration.

	Device No.	Device
	0	Environment
Productive	1	Generator
	2	Heat Exchanger
	3	Evaporator
	4	Solution Pump
Dissipative	5	Absorber
	6	Condenser

The various flows of the VAR system and their exergy values are listed in table 2. It should be noted that the table has the information required by TAESS to introduce both the characterization of flows and the productive structure.

Table 2. Definition of productive structure and exergy values introduced in the TAESS.

Flow	Exergy, E[kW]	Output Device	F/P	Input Device	F/P
1	65.00	1	P	6	F

International Journal of Advanced Technology in Engineering and Science
Vol. No.4, Issue No. 08, August 2016
www.ijates.com
ijates
ISSN 2348 - 7550

2	2.23	6	F	3	F
4	-149.00	3	F	4	F
5	58.00	4	F	5	P
6	61.00	5	P	2	P
7	77.00	2	P	1	P
8	398.00	1	P	2	F
9	359.00	2	F	4	F
11	2695.00	0	P	1	F
12	2055.00	1	F	0	F
13	17.716	0	P	3	P
14	88.65	3	P	0	F
15	19.58	0	P	4	P
16	56.00	4	P	6	P
17	109.00	6	P	0	F
18	7.00	0	P	5	F

2.4 THE FUEL-PRODUCT TABLE

The VARS can be represented in form of a diagram known as productive or functional diagram that defines the fuel and product distribution throughout the system. This diagram has the same units as that of the physical diagram, and a new set of flows *G*, such as a flow defined by the pair of components $(v_i \;\; v_j) \in G$ if the product of the component v_i becomes fuel of the component v_j. If E_{ij} represents the exergy carried out by this flow, the adjacency matrix of the graph is defined as:

$$G(i,j) = \begin{cases} E_{ij} \; if \; (v_i, v_j) \in G \\ 0 \; otherwise \end{cases}$$

(1)

The adjacency matrix could be represented by means of the Fuel-Product table, as explained by caudra [16]. The Fuel-Product table is a mathematical representation of the thermoeconomic model as shown in Table 3.

Table 3. Fuel-Product table.

	F_0	F_1	…	F_n
P_0		E_{01}	…	E_{0n}
P_1	E_{10}	E_{11}	…	E_{1n}
…	…	…	E_{ij}	…
P_n	E_{n0}	E_{1n}	…	E_{nm}

According to this representation, the production of one component (P_i) is used as fuel of other components or as a part of the total production of the VARS system.

$$P_i = E_{i0} + \sum_{j=1}^{n} E_{ij} \; , i = 0, 1, \ldots, n \qquad (2)$$

In the above expression, if the component is considered to be the system environment, then E_{i0} represents the production of the component ith that leaves the system as a final product or as a residue. On the other hand, the resources consumed by each component (F_i) could be written as:

$$F_i = E_{0i} + \sum_{j=1}^{n} E_{ji}, \quad i = 0, 1, \ldots, n \qquad (3)$$

Where E_{i0} represents the external resources used in the component.

III. EXERGY COST ANALYSIS

A key concept of thermoeconomics is exergy cost [17]. The exergy cost of a flow E is the amount of exergy needed to produce it, and it is represented by E^*. The unit exergy cost (k^*) is the ratio between the exergy cost and the exergy of the flow:

$$k^* = \frac{E^*}{E} \qquad (4)$$

E_{ij} is the part of the prduct of component i that becomes part of the fuel of component j. The unit exergy consumption is defined as the number of units of exergy that each component requires from the other component to obtain a unit of its product:

$$k_{ij} = \frac{E_{ij}}{P_j} \qquad (5)$$

The sum of all unit exergy consumptions in a component is the inverse of exergy efficiency of that component :

$$k_j = \sum_{i=0}^{n} k_{ij} = \frac{F_j}{P_j} \qquad (6)$$

The product of a component can be either a part of the plant product or a fuel to other components. Hence, by equations (2) and (6), exergy cost model can be written as

$$P_i = E_{i0} + \sum_{j=1}^{n} k_{ij} \, . \, P_j \qquad (7)$$

However, there are other flows which are necessary for the operation of the thermal system but do not have productive purpose. These flows are called wastes or residues and their cost has to be allocated to other components [14]. Hence, the cost balance of component i of a productive structure where wastes have been defined becomes:

$$P^* = F^* + R^* \qquad (8)$$

Where R^* is the cost of wastes assigned to that component. As a result, the unit exergy cost of the product is decomposed in two components [18]. The first is due to the irreversibilities ($k_p^{*,e}$) and the second to the residues ($k_p^{*,r}$).

$$k_p^* = k_p^{*,e} + k_p^{*,r} \qquad (9)$$

IV. RESULTS AND DISCUSSION

The thermoeconomic model, introduced in the first part of the paper, provides a productive scheme for each sub system of VARS. The values of the Fuel-Product table for thermodynamic states corresponding to the operation condition are presented in table 4. Each row represents how the product of a given component is distributed to others. For example 33 kW of product of generator go to the heat exchanger, 126 kW go the evaporator, 127 kW go to the absorber and 52 kW go to the condenser. The total product of generator is 386 kW. Similarly, each column represents the origin of fuel of each component. These results are applied as input data, to perform the exergy cost analysis presented in the later part of the paper.

Table 5 shows the values of fuel product, irreversibility and exergy costs for the six sub-systems of the VARS. From first three columns, it is obvious that how the irreversibility (I) is the difference between Fuel (F) and Product (P).The unit exergy consumption (k), as depicted in fourth column indicates that the most inefficient components are the absorber (k=4.1735) and the evaporator (k=2.1320). The unit exergy cost of the product (k_p^*) of a component is the sum of the cost of productive flow ($k_p^{*,e}$), and the waste flow ($k_p^{*,r}$). Last three columns shows how the exergy cost of product of each sub-system is equal to sum of the exergy cost of fuel (F^*) and the exergy cost of waste assigned to that sub-system (R^*).

Figure 3 represents graphically that how the unit exergy cost of the product of each subsystem is composed due to irreversibility appearing in the various sub-systems. The highest unit exergy cost appears in the absorber (8.8087). Heat exchanger has a small contribution in all other components except the generator. Irreversibility of generator has the highest contribution in all components. Whereas irreversibility of evaporator and absorber has only effect on its own exergy cost. Finally, the condenser has two contributions; one due to its irreversibility and the other because of the cost associated with the wastes.

Table 6 shows the Cost Fuel-Product table. This table has the same structure as fuel product table but using exregy cost, which is conservative. Hence, in each subsystem the exergy cost of the product (P^*) is equal to the sum of the exergy cost of fuel (F^*) and the cost of the waste (R^*) allocated to same component. For example, the exergy cost of the product of the generator is 750 kW which is distributed among the heat exchanger (63 kW), evaporator (245 kW), absorber (94 kW) and condenser(102 kW). Finally, this cost equals the summation of the exergy cost of the fuel of the generator (640 kW) and the exergy cost of the waste assigned to this component(110kW).

Table 4. Fuel-Product table for operation (kW).

DEVICE		F0	F1	F2	F3	F4	F5	F6	Product
Environment	P0	0	640	0	0	0	0	0	640
Generator	P1	0	0	33	126	127	48	52	386
Heat Exchanger	P2	0	0	2	6	6	2	3	19
Evaporator	P3	71	0	0	0	0	0	0	71
Absorber	P4	36	0	0	0	0	0	0	36
Solution Pump	P5	0	0	5	19	19	7	8	58
Condenser	P6	53	0	0	0	0	0	0	53
Fuel	F	107	640	39	151	152	58	63	
Residue	R	53	0	0	0	0	0	0	

Table 5. Fuel, Product, Irreversibility and Cost of operation

	F	P	I	k	k_P^e	k_P^r	k_P	k_F	P^*	F^*	R^*
1	640	386	254	1.66	1.66	0.29	1.94	1.00	750.45	640.00	110.45
2	39	19	20	2.05	3.59	1.03	4.62	2.11	87.75	82.31	5.44
3	151.23	70.93	80.30	2.13	3.73	0.77	4.50	2.11	319.19	319.19	0
4	152	36.42	115.58	4.17	7.30	1.51	8.81	2.11	320.81	320.81	0
5	58	58	0	1	1.75	0.65	2.40	2.11	139.01	122.42	16.60
6	62.77	53	9.77	1.18	2.07	0.43	2.50	2.11	132.48	132.48	0

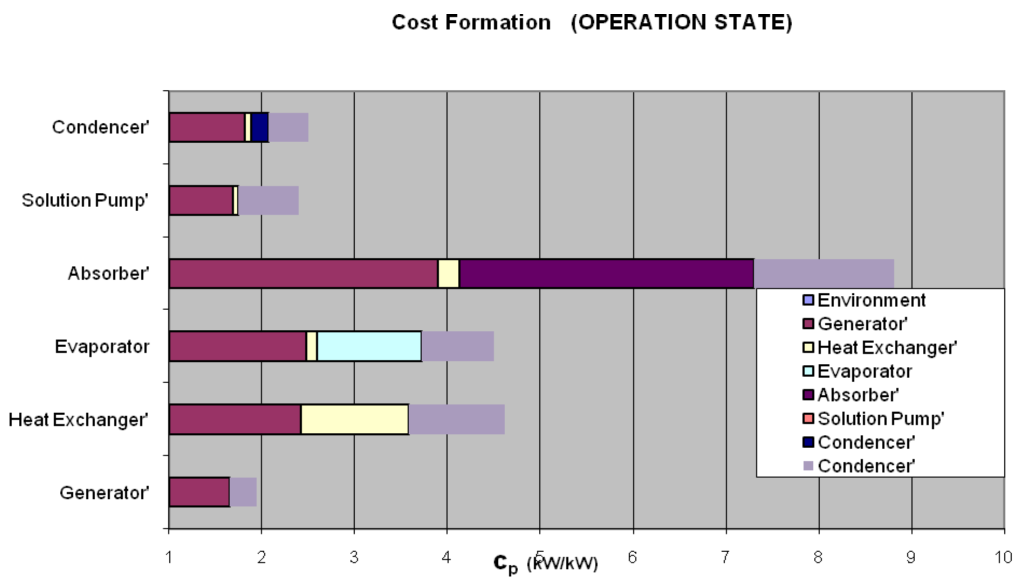

Figure 3. Unit Cost decomposition for operation

Table 6. Cost Fuel-Product table for operation (kW).

DEVICE		F0*	F1*	F2*	F3*	F4*	F5*	F6*	P*
Environment	P0*	0	640	0	0	0	0	0	640
Generator	P1*	0	0	63	245	246	94	102	750
Heat Exchanger	P2*	0	0	7	29	29	11	12	88
Evaporator	P3*	319	0	0	0	0	0	0	319
Absorber	P4*	321	0	0	0	0	0	0	321
Solution Pump	P5*	0	0	12	45	46	17	19	139
Fuel	F*	640	640	82	319	321	122	132	
Condenser	P6*	0	110	5	0	0	17	0	132
Residue	R*	0	110	5	0	0	17	0	

V. CONCLUSION

This research paper applied *exergy cost analysis* to enhance the utilization of energy resources for a single stage vapour absorbtion refrigeration system (VARS). This method also provides cost allocation of residues and the analysis of their formation process.

Fundamental concept is the analysis of interactions between various subsystems of VARS and defining their detailed productive structure to build the Fuel-Product table of whole VARS for a given thermodynamic state. Fuel product table is a mathematical representation of productive structure graph and provides functional requirement for the analysis of exergy cost analysis. The concept of exergy cost provides the formulae describing the cost formation process for a given system and is applied for the optimization problem.

In this analysis, various parameters of inefficiencies are obtained to measure the irreversibilities causing the reduction of efficiency. As supported by earlier work, this study verifies the essential features of the thermoeconomic modeling. It not only predicts the resources consumed by VARS but can also explain the responsibility of each subsystem of VARS.

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VI. ACKNOWLEDGEMENTS

The authors are grateful to Prof. Suresh Jain for his valuable guidance and encouragement.

VII. NOMENCLATURE

A	Absorber
C	Condenser
E	Exergy of a flow (kW)
E^*	Exergy Cost of a flow (kW)
ER	Refrigerant expansion valve
ES	Solution expansion valve
EV	Evaporator

F	Exergy of fuel (kW)
G	Generator
HE	Solution heat exchanger
I	Irreversibility (kW)
k^*	Unit exergy cost (kW/kW)
k_P^*	Unit exergy cost of product (kW/kW)
$k_P^{*,e}$	Unit production cost due to irreversibilities (kW/kW)
$k_P^{*,r}$	Unit production cost due to residues (kW/kW)
$k_P^{*,e} . \Delta P_e$	Final product cost variation (kW)
$k_P^{*,r} . \Delta P_r$	Residue cost variation (kW)
m	Number of flows
n	Number of components
P	Exergy of product (kW)
Q	Heat flow rate (kW)
SP	Solution pump
T	Temperature (ºC or K)
v_i	i^{th} Component of the system
W	Mechanical power (kW)

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