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Advanced Exergy Assessment of an Air Source Heat Pump Unit

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Abstract
Energy conversation systems performance could be assessed by conventional exergy-based analysis methods. Along with the conventional exergy approach, the sources and amounts of the exergy destructions can be determined, and a possible direction for enhancement can be suggested. Nevertheless, interactions between system components (endogenous/exogenous) and technical constraints (avoidable/unavoidable) cannot be identified with any conventional analysis. Therefore, the real potential to improve and optimize can be misdirected. The advanced exergy-based analysis seeks to overcome this limitation. An air-source heat pump unit was assessed using conventional and advanced exergy analysis approaches, respectively. Avoidable/unavoidable and endogenous/exogenous exergy destructions, modified exergy efficiencies, and modified exergy loss ratios were calculated for every single component of the system. The results of the analysis showed that while the evaporator and condenser efficiencies could be improved through design improvements, the internal operating conditions were mainly responsible for the inefficiencies associated with the compressor. The analysis indicated that it was possible to improve evaporator and condenser efficiency by making design improvements. The efficiency of the compressor was mainly determined by the internal conditions in which the compressor operated.

1. Introduction

The two most important problems of the in the not-too-distant past are energy shortages arising from overuse and ecological contamination. Therefore, existing energy resources must be used more effectively and economically; otherwise enhanced exergy approaches should be employed more widely in thermal systems. The largest contributor to household energy consumption is residential space air conditioning, along with the processing of domestic hot water. According to the study of Jung et al. [1], energy demand for heating and cooling buildings is predicted to rise by up to 50% by 2050 as energy consumption grows in many regions.

Heat pumps (HPs) are an emerging technology that is gaining popularity in heating and air conditioning around the world due to their environmentally favorable and efficient use of energy in comparison to standard systems. Exergy analysis is a very powerful method that can be efficiently applied to the design of an energy system. Also, this method provides essential knowledge for selecting the appropriate design parameters of the components and the mode of operation [2]. Conventional exergy-based methodologies are utilized to measure the effectiveness of thermal energy conversion systems. Traditional exergy-based analysis reveals the sources, amounts, and reasons for irreversible losses (exergy losses), costs, and environmental effects and identifies a broad area for enhancement. But interactions between system components and current technical restrictions cannot be identified with any of the conventional analyses. Therefore, a more effective way to improve energy conversion systems is to separate the exergy destruction that occurs in every single component of

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the system. This limitation could be removed by implementing advanced exergy-based analyses. A more complex exergy analysis where exergy destruction is separated into avoidable, unavoidable, exogenous, and endogenous parts is called advanced exergy analysis [3].

By implementing the enhanced exergy approach to a military turbojet engine, the types of exergy destruction in the system were determined, and it was found that elements of the jet engine related to ignition should be improved [4]. Chen compared the refrigeration system of the ejector and the vapor compression refrigeration system, performing an enhanced exergy approach [5]. Morosuk and Tsatsaronis [6] investigated the efficiency of an absorption refrigeration machine by implementing the advanced exergy analysis approach. Endogenous avoidable and exogenous avoidable exergy destruction values are remarkable in improving the components in the system one by one. In the study, it is recommended to make an advanced exergoeconomic evaluation by calculating the exergy destruction as well as the initial investment costs by dividing them into sections. The advanced exergy and exergoeconomy analysis methods performed by Vuckovic et al. [7], for a real industrial facility. It was revealed that the performance of the system would be improved by enhancing the operating parameters of the boiler. The natural gas liquefaction and production facilities are evaluated regarding advanced exergoeconomic and exergy analysis, and it is revealed that most of the exergy destruction was exogenous and the exergy destruction in other units was endogenous. The researchers also found that endogenous exergy destruction leads to the greatest costs, according to the results of the exergo-economic analysis [8]. Hepbaşlı and Keçebaş [9] implied an advanced exergy analysis method to assess the improvement potential of a geothermal-sourced central heating system and to reveal the contribution of the system components to this improvement potential rate. The significance of exergy analysis has been increasing in recent years in order to ensure efficient and effective use of energy. With conventional exergy analysis, the location, size, cost, and environmental effects of irreversibility are determined, and general improvements are recommended accordingly. Yet, this information is not sufficient for the presentation of certain insights. In order to identify the realistic potential and to deduce how to improve, advanced exergy analysis based on the splitting of exergy losses should be carried out. The reason for this is that, given the present state of knowledge, some portion of the exergy destruction could be unavoidable (defined by the division of exergy losses into unavoidable and avoidable fractions), some may be a consequence of exergy losses on the rest of the components of the present thermal system under consideration (exogenous exergy destruction), and therefore, rather than just improving the component with the largest exergy destruction, it may be valuable to enhance the rest of the components [10]. To overcome the above drawbacks, extended exergy analysis has been suggested. The division of exergy destructions into avoidable endogenous, unavoidable endogenous, avoidable exogenous, and unavoidable exogenous in advanced exergy analysis enables it to yield insightful results that conventional exergy analysis cannot. [11].

In the present study, an air source heat pump test unit was installed in the laboratory of Manisa Celal Bayar University, Türkiye, while it was examined through conventional and advanced exergy analysis methods under experimental conditions. First, the exergy destruction rate, the exergy efficiency coefficient, the relative irreversibility, and the enhancement possibility of the individual system components were computed with the conventional exergy analysis approach. After that, advanced exergy analyses were conducted by dividing the exergy destructions into parts. In this regard, the objectives of the current study are to apply advanced exergy analysis to the heat pump unit for further understanding of the exergy destruction rates and then to reveal the possible improvement rate.

2. Material and Method

2.1. Experimental Heat Pump Unit

As the problems associated with energy efficiency and environmental pollution have gradually increased, the number of studies focusing on these issues has also significantly increased in recent years. HP technologies are recognized as important and environmentally friendly and have been used for many years in climate control applications (particularly heating and cooling). In this regard, an experimental setup of an air source heat pump unit has been operated at Manisa Celal Bayar University, Manisa, Türkiye. The conventional exergy and advanced (enhanced) exergy approaches regarding dividing the exergy destructions into unavoidable/avoidable and exogenous/endogenous sections have been performed. The modified illustration of the heat pump system appears in Figure 1.

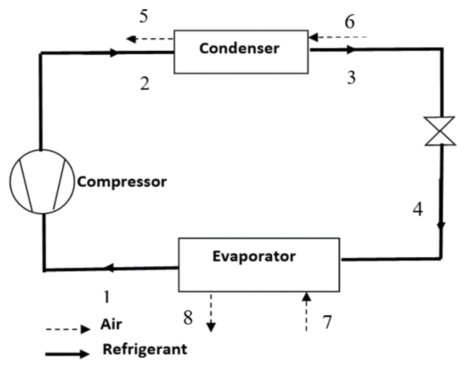

Figure 1. Schematic flow diagram of the air source heat pump system.

Figure 1 shows a schematic diagram of the HP system, which comprising compressor, condenser, expansion valve, and evaporator.

The assumptions used in the analysis are set out below:

(a) As there are no chemical transformations, all processes are in a steady state, and changes in potential and kinetic energy are ignored.

(b) The loss of heat in the heat exchangers is regarded as being of insignificant importance.

(c) The compressor operates adiabatic and irreversibly; the isentropic efficiency is taken as 0.85.

(d) The dead-state temperature is estimated at 10°C, and the pressure is taken at 101.325 kPa for the analysis.

2.2 Conventional Exergy Analysis

In the design and development of systems, exergy analysis is essential as it can indicate the location, type, and amount of exergy destruction and losses. With exergy analysis, the location and size of irreversibility (entropy generation) in a system can be determined, and development and improvement studies can be carried out to reduce irreversibility.

General exergy equations are employed for all system components on a component basis and then for the whole system. At the component level, the exergy product rate ($\dot{E}_{P,k}$) can be defined as the exergy output obtained per unit time, and the exergy fuel rate ($\dot{E}_{F,k}$) can be defined as the input provided to obtain the desired exergy output per unit time. The difference between the exergy fuel rate and the exergy product rate is identified as the exergy destruction rate in the system per time period. The coefficient of exergy efficiency and exergy destruction can be obtained from the standpoint of the exergetic product and the exergetic fuel, while the conventional exergy balance can be explained as follows for the component *k*th [12]:

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \quad (1)$$

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \quad (2)$$

Other useful concepts such as "improvement potential" (IP), "exergetic factor" (f) and "relative irreversibility" (RI) are used to assess the effects of the system components on the whole system.

$$IP = (1 - \varepsilon)(\dot{E}_g - \dot{E}_ç) \quad (3)$$

$$f = \frac{\dot{E}_{F,k}}{\dot{E}_{F,total}}.100 \quad (4)$$

$$RI = \frac{\dot{E}_{D,k}}{\dot{E}_{D,total}}.100 \quad (5)$$

The principle of sustainability is consistent with the management of resources in terms of social, natural, and economic aspects. With environmental and cost control issues, it has become more important. A useful indicator for measuring the sustainability of the framework is the sustainability index. The exergetic sustainability index can be estimated on the basis of [13]:

$$SI = \frac{1}{1-\varepsilon_k}.100 \quad (6)$$

2.3 Advanced Exergy Analysis

Conventional exergy analysis can be used to determine the sources, positions, and amounts of irreversibilities in a system and to suggest general improvements to the system. However, none of the conventional exergy analysis methods can be used to calculate the irreversibility resulting from the interaction between system components. Also, conventional exergy analysis is insufficient to reveal the realistic improvement potential due to current technological limitations. Splitting the exergy destruction into parts allows further understanding of the exergy destruction causes. Thereby, the accuracy of the analysis could be enhanced. In advanced exergy analysis, exergy destructions can be split into their endogenous and exogenous and/or avoidable and unavoidable parts [14]. Endogenous exergy destructions ($\dot{E}_{D,k}^{EN}$) for a component of the system are defined as the destructions that are independent of the other components of the system.

In order to estimate endogenous exergy destructions, it is assumed that every component of the system runs under theoretical circumstances, whereas the component under consideration is performing with the same level of efficiency as in the actual system. The inefficiencies caused by the other system components are indicated by the exogenous exergy destruction of one system component. The exogenous exergy destruction ($\dot{E}_{D,k}^{EX}$) of one component of the system indicates irreversibilities that are imposed by the other components of the system.

Endogenous and exogenous exergy destruction is calculated using the following equations:

$$\dot{Ex}_{d,k}^{real} = \dot{Ex}_{d,k}^{EN} + \dot{Ex}_{d,k}^{EX} \quad (7)$$

$$\dot{Ex}_{d,k}^{EN} = \dot{Ex}_{P,k}^{real} x \left(\frac{\dot{Ex}_{d,k}}{\dot{Ex}_{P,k}}\right)^{EN} \quad (8)$$

Exergy destruction, costs, and environmental impacts that can be prevented by technically appropriate design and/or operational improvements in a system are considered the avoidable part of the exergy destruction. Determining the amount of avoidable exergy destruction in a system plays an important role in emphasizing the steps to be taken for the improvement of efficiency in the whole system. The remaining exergy destruction, which cannot be destroyed by any physical or technological development, is also considered unavoidable exergy destruction [15], [16]. In order to determine the unavoidable exergy destruction, it is assumed that the components of the system are operating at their maximum efficiency according to the current state of technology.

The expressions for the determination of unavoidable and avoidable exergy destructions are given [17]:

$$\dot{E}_{d,k}^{UN} = \dot{E}_{P,k}^{real} . \left(\frac{\dot{E}_{d,k}}{\dot{E}_{P,k}}\right)^{UN} \quad (9)$$

$$\dot{Ex}_{d,k}^{real} = \dot{Ex}_{d,k}^{UN} + \dot{Ex}_{d,k}^{AV} \quad (10)$$

In addition, the modified exergy efficiency coefficient is computed by means of the formula:

$$\varepsilon_k^* = \frac{\dot{Ex}_{\mathrm{P,k}}^{\mathrm{real}}}{\dot{Ex}_{\mathrm{F,k}}^{\mathrm{real}} - \dot{Ex}_{\mathrm{D,k}}^{\mathrm{UN}}} \mathrm{x}\ 100 \quad (11)$$

Once avoidable/unavoidable and exogenous / endogenous exergy destruction currents are found for all system components, these values are associated with avoidable (AV) and unavoidable (UN) exergy destruction values to obtain useful new terms. One can identify the irreversibility's regarding with the system component itself that can be removed by computing the avoidable endogenous exergy destruction.

$$\dot{E}_{D,k}^{UN,EN} = \dot{E}_{P,k}^{EN} . \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN} \quad (12)$$

$$\dot{Ex}_{d,k}^{UN,EX} = \dot{Ex}_{d,k}^{UN} - \dot{Ex}_{d,k}^{UN,EN} \quad (13)$$

Furthermore, the calculation of avoidable exogenous exergy destruction can highlight the irreversibility's that can be eliminated by structural enhancements to the entire system or by enhancing the performance of the residual elements and increasing the performance of the component under consideration.

$$\dot{Ex}_{d,k}^{AV,EN} = \dot{Ex}_{d,k}^{EN} - \dot{Ex}_{d,k}^{UN,EN} \quad (14)$$

$$\dot{Ex}_{d,k}^{AV,EX} = \dot{Ex}_{d,k}^{AV} - \dot{Ex}_{d,k}^{AV,EN} \quad (15)$$

3. Results and Discussion

This study evaluated an air source heat pump system based on the conventional exergy method using advanced exergy analysis and the division of the exergy destruction rates into different parts for the experimental values. Experimental data and calculations of the heat pump unit are shown in Table 1. Conventional exergy analysis parameters such as fuel exergy and product exergy rates for the whole system are shown in Table 2. Also, it shows exergetic parameters such as the exergy efficiency, improvement potential rate, exergy factor, sustainability index, relative irreversibility, and exergy destruction rates for the system components. The evaporator, followed by the compressor and the condenser, had the greatest exergy destruction rates. Moreover, the compressor and the expansion valve exergetic efficiency values demonstrated that these components have the highest value compared to other components. The exergetic improvement potential rate obtained was 1.618 for the whole unit. According to the exergetic factor (*f*) of the heat pump unit, the compressor and evaporator exhibit the greatest quantities of exergetic fuel rate, obtaining 36.97% and 27% of the total exergy fuel rate in the system, respectively. Regarding the relative irreversibility of the air-source heat pump system subcomponents, the condenser has the lowest *RI* rate at 13.84%, and the evaporator has the highest rate at 57.47% due to its high irreversibility and low efficiency. The exergetic sustainability index (SI) values of the system and components are also given in Table 2. The evaporator has the lowest SI rate at 1.29, followed by the condenser at 1.36, since these components cause more exergy destruction than other components.

Table 1. The thermodynamic specifications determined from experimental data.

State	$\dot{m}$(kg/s)	T (°C)	h (kJ/kg)	s (kJ/kgK)	ex (kj/kg)
1	0.082	24	274.80	1.074	7.602
2	0.082	90.06	326.91	1.096	53.490
3	0.082	38	275.80	0.951	43.316
4	0.082	-5.3	275.80	0.974	36.775
6	0.638	22.1	33.79	-	0.255
7	0.638	25.7	37.44	-	0.425
8	0.638	20.7	31.73	-	0.177

A conventional exergy analysis can show the distribution of exergy destruction and the maximum exergy destruction ratios between individual components. It cannot identify the magnitude of the interactions between system components and the opportunities for improvement. Exergy destructions within a component are divided into categories such as endogenous/exogenous and avoidable/unavoidable in advanced exergy analysis. This method makes it possible to better identify the origins of thermodynamic inefficiency. This also makes it possible to refine and optimize the overall system. This approach specifies the exogenous exergy destruction with the effects of the interactions between the elements while estimating the endogenous exergy destruction with the operational losses within the component. In addition, technological and physical limitations on the efficiency of the system constitute unavoidable exergy destruction. Table 3 summarizes the conclusions of the advanced exergy approach of the present heat pump unit.

Table 2. The calculations of conventional exergy analysis.

Component	$\dot{E}_{F,k}$ (kW)	$\dot{E}_{P,k}$ (kW)	$\dot{E}_{D,k}$ (kW)	ε (%)	$I\dot{P}$ (kW)	RI (%)	SI	f (%)
I Compressor	4.500	3.763	0.737	83.62	0.121	16.61	6.10	36.97
II Condenser	0.834	0.220	0.614	26.38	0.452	13.84	1.36	6.85
III Expansion valve	3.552	3.016	0.536	84.90	0.081	12.08	6.62	29.18
IV Evaporator	3.287	0.736	2.551	22.40	1.979	57.47	1.29	27.00
Overall system	12.173	7.735	4.438	63.54	1.618	100.00	2.74	100.00

Table 3. Advanced exergy approach findings of heat pump unit.

Component	$\dot{E}_{D,k}^{EN}$ (kW)	$\dot{E}_{D,k}^{EX}$ (kW)	$\dot{E}_{D,k}^{UN}$ (kW)	$\dot{E}_{D,k}^{AV}$ (kW)	$\dot{E}_{D,k}^{UN}$ (kW)		$\dot{E}_{D,k}^{AV}$ (kW)	
					$\dot{E}_{D,k}^{UN,EN}$ (kW)	$\dot{E}_{D,k}^{UN,EX}$ (kW)	$\dot{E}_{D,k}^{AV,EN}$ (kW)	$\dot{E}_{D,k}^{AV,EX}$ (kW)
I Compressor	0.511	0.226	0.245	0.491	0.375	-0.134	0.135	0.360
II Condenser	0.117	0.497	0.185	0.428	0.885	-0.532	-0.768	1.029
III Expansion valve	0.458	0.077	0.498	0.037	0.430	0.163	0.027	-0.085
IV Evaporator	0.342	2.208	1.356	1.194	2.00	0.359	-1.666	1.849
Overall system	1.429	3.009	3.059	1.380				

When considering the whole system on the basis of running operation, the unavoidable exergy destruction ($\dot{E}_{D,k}^{UN}$) is calculated to be 3.059 kW. Contrary, the avoidable exergy destruction ($\dot{E}_{D,k}^{AV}$) is estimated to be 1.380 kW for the overall system. Referring to the results for the evaporator, it has the highest unavoidable exergy rate $\dot{E}_{D,k}^{UN}$ with the rates of 1.356 kW. This rate consist % 44.33 of unavoidable exergy destruction within in the heat pump unit. The maximum $\dot{E}_{D,k}^{AV}$ value is estimated to be 1.194 kW for the evaporator and 0.491 kW for the compressor. Considering the calculation of the endogenous/exogenous exergy destruction rate, the total endogenous exergy destruction is calculated to be 1.429 kW whereas the overall exogenous exergy destruction ($\dot{E}_{D,k}^{EX}$) is estimated as 3.009 kW. Figure 2 is an illustration of the distribution of exergy destructions in the overall system and its main units.

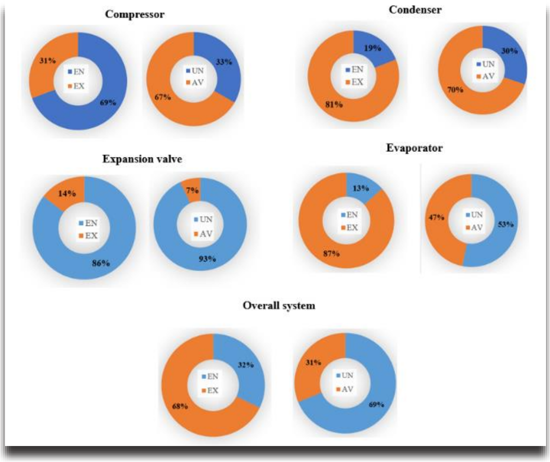

Figure 2. The exergy destruction rates the air source heat pump unit.

Internal exergy destructions so-called endogenous exergy rate at the compressor has substantial 69.0% of sum exergy destructions were considered as endogenous (Fig. 2), meaning that from a design perspective, compressor inefficiency could be autonomously lowered. In addition, more than half (67.0%) of the total avoidable endogenous exergy destruction was attributed to the compressor. Figure 2 shows that both exogenous and avoidable exergy destructions within the condenser were very high. Exogenous and avoidable exergy destructions were in the range of 81.0% and 70.0% of the total exergy destructions, respectively. Therefore, it can be concluded that the inefficiencies within the condenser are largely affected from the other components of the heat pump unit. From Figure 2 one can notice that three-fourths of the entire exergy destroyed in the evaporator was exogenous. Furthermore, almost half of the total evaporator destruction was avoidable exogenous exergy destruction. All of these results indicate that efforts to reduce evaporator inefficiencies should focus primarily on component interactions.

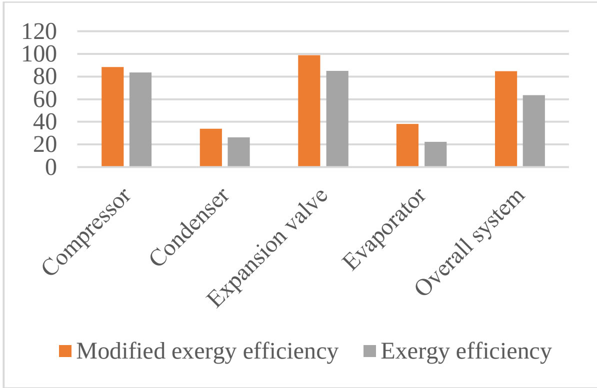

Figure 3. A comparison of the exergy efficiency and the modified exergy efficiency.

While the exergy efficiency of the compressor was 83.61%, the modified exergy efficiency was not increased too much and calculated 88.44%. The conventional exergy efficiencies of the evaporator and condenser were 22.44% and 26.37% when the modified exergy efficiencies were obtained as 38.13% and 33.91%, respectively.

4. Conclusion and Suggestions

The conventional and advanced exergy analyses of an air-source heat pump unit have been performed in this study. The elements of the system were assessed individually, and the following are the main observations that can be derived from the findings of the current study:

- The proportion of unavoidable exergy destruction is found to be highest at 53% for the evaporator, while the condenser has the minimum proportion at 30%. These results show that the range of potential improvements to the evaporator is limited.
- The share of endogenous exergy destruction in total destruction is highest for the compressor (69%). This means that this component is not directly impacted by the operating conditions of the other components.
- The exergy efficiency of the heat pump unit is estimated at 63.54%, according to the experimental data.
- In view of the findings of the advanced exergy analysis, the condenser and compressor components should take priority for the enhancement efforts of the whole system.

For further studies, advanced exergy assessment methods can be used to evaluate other thermal systems, such as trigeneration plants.

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Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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