Thermoeconomic Analysis of a Mobile Air Conditioning Unit Using the Specific Exergy Cost (SPECO) Method

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Abstract. In recent years, many researchers have used exergy-based analysis and assessment methods such as exergy, exergoeconomic and exergoenvironmental as powerful tools to solve practical problems in the design and to improve energy-related systems. The main objectives of this contribution are to analyse and assess the performance of a mobile air conditioning (MAC) system from the thermoeconomic point of view that combines energy quality and economic issues. We used the specific exergy cost (SPECO) method to calculate exergy-related parameters and display cost flows for all streams and components in the whole system. In this context, we considered a vapour compressed MAC unit (utilizing R134a as a refrigerant) of a public bus with a capacity of 99 passengers and a volume of 69 m³. In the analysis, we utilized the real data obtained from the measurements. Based on the exergetic analysis, while the highest exergy destruction rate was determined to be 3.7 kW for the compressor, with a minimum value of 0.15 kW due to the condenser unit. Furthermore, through the SPECO method, the highest and lowest exergoeconomic factors belonged to the condenser with 0.63 and the expansion valve with 0.05, respectively.

1. Introduction

Air conditioning (AC) systems have been used in a wide range of applications and are of great importance in transportation sector. More energy efficient solutions in mobile air conditioning (MAC) units have become very essential while meeting thermal comfort conditions. In this regard, improving the energy efficiency of a MAC system has been a leading topic in a mobile industry due to fuel saving and climate change. The MAC system indicates two distinctive features compared to the residential air-conditioning system. The first one is some extreme limitations to the space and weight while the second one is changing the thermal load of the cabin dramatically. This means that MAC systems should be carefully designed, so that they could be operated under a wide range of conditions [1].

Beside the design issues of MAC systems, their performance assessment plays a key role. In the literature, various studies on MAC systems have been reported. The performance of these units have been mostly evaluated through energy-based analysis methods (e.g., [2]). To get the complete picture of a system, a thermodynamic investigation needs to include both energy and exergy analyses. Application of exergy-based analysis methods to various energetic systems and processes has been recently very attractive due to identification of exergy losses and deduction of possible improvement potentials on them.
Exergy covers both the quantity and quality of energy. The term 'exergoeconomics' has been used in Europe while that 'thermoeconomics' has been preferred in the United States. Exergoeconomic analysis combining exergy analysis method with economics offers useful information on the thermodynamic and economical interrelations. It also provides the system designer or operator with information, which is obtained from conventional energy analysis and economic evaluations, but very essential to the design and operation of a cost-effective system [2]. In this regard, different researchers have proposed various thermoeconomic (exergoeconomic) approaches, methods, or techniques. Among these, the specific exergy cost (SPECO) method has been widely used. As reported in [3] and [4], there are very limited studies on exergetic assessment of MAC units based on actual operational data. In this context, Tosun et al. [3] applied exergy analysis method to an inter-city bus AC system with a passenger capacity of 56 people for improvement purposes. They reported that exergy efficiencies of the refrigeration system ranged from 25.7% to 28.4%. Ozcan et al. [3] studied on both conventional and low exergy analyses of a public bus along with its air conditioning unit. They determined that the water heat exchanger had the greatest exergy efficiency of 93.28% while the lowest one of 72.16% belonged to the pump in the heating mode.

The authors have extended their study by applying the SPECO method to the air conditioning unit of a public bus, being differently from their previous studies conducted. In this context, the main objectives of this contribution are to (i) determine exergy rates of all streams, (ii) investigate all component and streams using the SPECO method, and (iii) evaluate the performance of the MAC unit and its cost dimensions.

2. System description
In this study, a vapour compressed MAC unit with a capacity of 38 kW is regarded for the thermoeconomic analysis. As can be seen from figure 1, the main components located in the unit are as follows: I - an open type engine driven compressor, II – a condenser unit (finned tube heat exchanger and axial fans), III - an external pressure equalized expansion valve and IV – an evaporator unit (finned tube heat exchanger and blower fans). Besides, a liquid tank, a sub cooling coil, a drier, a sight glass and a superheating coil are taken part in the MAC unit, enabling a safe operation of the refrigeration cycle. While the rest of the auxiliary components rather than super heating coil are used between the condenser unit and the expansion valve to provide fully a pure and clean liquid phase entering the expansion valve, the super heating coil is located before the open type compressor to ensure fully a vapour refrigerant flow within this component.

![Figure 1. MAC unit (adapted from Ref. [4])](image-url)
As shown in the figure given above, the refrigeration cycle was applied by employing R134a as the refrigerant for conditioning the bus indoor air to provide comfort conditions for occupants. Within this scope, when the bus starts running, the open type vapour compressed compressor starts to work via belt driven by the bus engine. This causes the refrigerant to warm up and increase its pressure before the condenser unit. Then, while this refrigerant passes through the condenser coils, the ambient air flows outside of these coils by axial fans, allowing the heat interaction between two fluids, namely the refrigerant and the air.

On the refrigerant side, this process enables to condense by rejecting heat to the air, which brings a lower temperature and almost the same pressure values for the refrigerant before the expansion valve. Then, the external pressure equalised the expansion valve has to be completely supplied with a pure and clean liquid phase refrigerant. For this reason, the liquid tank (splitting liquid and gas phases), the subcooling coil (condensing excess vapour to liquid), the drier (trapping moisture and dust) and the sight glass (used to observe flow conditions) are taken part before this component. Unlike the compressor, the expansion valve provides the refrigerant to cool down and decrease its pressure before the evaporator unit. In this unit, while the refrigerant flows through the coils, the bus indoor air passes outside these coils by blower fans, allowing the heat interaction between two fluids, namely the refrigerant and the air. On the refrigerant side, this process enables the refrigerant to evaporate by absorbing heat from the air side. Later on, the refrigerant gets a higher temperature and almost the same pressure values before the compressor. After that, the refrigerant passes through the superheating coil to provide completely a vapour phase for the compressor. At the end of these stages, the refrigerant reaches its initial state and the cycle is completed. Throughout this process, energy consumption from the bus engine, the heat rejection to the atmospheric air and conditioning the bus indoor air are all provided.

3. Analyses
The considered system shown in figure 1 was analysed and evaluated using the thermoeconomic analysis method considering the main components, namely, the compressor, the condenser unit, the expansion valve and the evaporator unit. In this context, three interrelated methods were applied to the considered system for determining both energetic and exergetic performances along with an economic evaluation. Firstly, the energy analysis was carried out based on the real data obtained from the measurements made in a company [6]. The derived equations are indicated in table 1 where the energy balance for each component represents the energy inlet and outlet flows enabling to calculate energy losses (equation (1)) and the exergy efficiency (equation (2)) in terms of quantity of energy [6]. As can be seen from the equations in the table, while the compressor and the expansion valve were only considered based on the refrigerant side, the condenser and the evaporator units were analysed considering both the refrigerant and air sides.

\[
\dot{E}_{loss} = \dot{E}_{in} - \dot{E}_{o} \tag{1}
\]
\[
\eta = \frac{\dot{E}_{o}}{\dot{E}_{in}} \tag{2}
\]

Secondly, the exergy balance equations were derived for each component for calculating the exergy destruction rates (equation (3)) and the exergy efficiency (equation (4)), in terms of quality of energy. In this regard, fuel and product exergy rates were computed first as shown in equation 1. In this analysis method, while the exergetic fuel rates are always spent, the exergetic product rates always exhibit an increased behaviour [7]. For determination of energetic and energetic performances, the thermophysical properties of R134a and air were obtained from the thermodynamics and transport properties database (REFPROP) program [8].

\[
\dot{E}_{x_{des}} = \dot{E}_{x_{F}} - \dot{E}_{x_{P}} \tag{3}
\]
\[
\psi = \frac{\dot{E}_{x_{P}}}{\dot{E}_{x_{F}}} \tag{4}
\]
After completing the energetic and exergetic evaluation, the SPECO method was applied to the system under consideration that had a capital investment cost of 3,500 €. The cost distribution was determined to be 1,793.75 € for the compressor, 685.41 € for the condenser, 230.41 € for the expansion valve and 790.41 € for the evaporator. In this approach, the exergy balances given in Table 1 were combined with the calculated costs based on the basic principles from business administration. In this regard, the exergy streams were associated with the cost interactions by using equations (5)-(9) given below for the kth component receiving a heat transfer and generating the power. In general, if there are more than one exergy outlet stream within the kth component, one needs exergy outlet streams – 1 auxiliary equations, namely F and P principles for solving equation (9) under the condition that knowing exergy inlet streams [9].

\[ \dot{c}_\text{in} = c_\text{in} \dot{E}_\text{in} = c_\text{in} \dot{m}_\text{in} e_x \text{in} \]  \hspace{1cm} (5)  
\[ \dot{c}_\text{a} = c_\text{a} \dot{E}_\text{a} = c_\text{a} \dot{m}_\text{a} e_x \text{a} \]  \hspace{1cm} (6)  
\[ \dot{c}_\text{w} = c_\text{w} \dot{W} \]  \hspace{1cm} (7)  
\[ \dot{c}_q = c_q \dot{E}_x \]  \hspace{1cm} (8)  
\[ \sum_o (c_0 \dot{E}_x)_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}_x q,k + \sum_{\text{in}} (c_\text{in} \dot{E}_x \text{in})_k + \dot{Z}_k^T \]  \hspace{1cm} (9)  

Moreover, the hourly levelized total cost of the kth component (\( \dot{Z}_k^T \)) can be calculated by applying six main steps given as follows. In this regard, the present worth rate (€/h), the salvage value rate (€/h), the present worth factor (-), the annual capital cost (€/h) and the capital recovery factor (-) should be determined, respectively [9].

\[ PW_{MAC} = \dot{c}_\text{MAC} - S_{MAC}PWF(i,n) \]  \hspace{1cm} (10)  
\[ S_{MAC} = \dot{c}_\text{MAC}j \]  \hspace{1cm} (11)  
\[ PWF = \frac{1}{(1+i)^n} \]  \hspace{1cm} (12)  
\[ C\dot{A}_{MAC} = PW_{MAC}CRF(i,n) \]  \hspace{1cm} (13)  
\[ CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \]  \hspace{1cm} (14)  
\[ \dot{Z}_{MAC}^T = \frac{C\dot{A}_{MAC}}{\tau} \]  \hspace{1cm} (15)  

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**Table 1. Energy and exergy balances [6]**

| Main components | Energy balance (W) | Exergy balance (W) |
|-----------------|--------------------|--------------------|
| Compressor      | E_{\text{comp}} = W_{\text{comp}} + E_{r,\text{comp}} |
| Condenser       | E_{\text{cond}} = E_{r,\text{cond}} + E_{a,\text{cond}} |
| Expansion valve | E_{\text{expv}} = E_{r,\text{expv}} |
| Evaporator unit | E_{\text{evap,oa}} = E_{r,\text{evap,oa}} + E_{a,\text{evap,oa}} |

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As the exergy destruction and the second law (exergy) efficiency values are used for the exergetic performance evaluation of the considered system, the exergoeconomic factor and the relative cost difference determine the thermoeconomic performance [11], which are defined by

\[
\frac{\dot{Z}_{k,CI}}{Z_{k,MAC}} = \frac{\dot{PEC}_k}{\sum_{MAC} \dot{PEC}_k},
\]

\[
\dot{Z}_{k,OM} = \frac{\dot{PEC}_k}{\sum_{MAC} \dot{PEC}_k}, \quad \dot{Z}_k = \dot{Z}_{k,CI} + \dot{Z}_{k,OM}
\]

As the exergy destruction and the second law (exergy) efficiency values are used for the exergetic performance evaluation of the considered system, the exergoeconomic factor and the relative cost difference determine the thermoeconomic performance [11], which are defined by

\[
f_k = \frac{\dot{Z}_k}{\dot{Z}_{k,MAC} + \dot{C}_{des,k}}, \quad r_k = \frac{1 - \psi_k}{\psi_k} + \frac{\dot{Z}_k}{\dot{C}_{des,k}}
\]

While applying the three interrelated methods for the considered system, some assumption made are listed as follows:

- The MAC unit operates at steady state condition with 40.80 °C and 101.32 kPa reference state values.
- The electrical and mechanical efficiencies of the compressor are 0.95 and 0.80, respectively.
- The effectiveness values of the condenser and evaporator units are 0.90.
- The isenthalpic process is considered for the expansion valve.
- The mass flow rate of R134a is calculated from the condenser unit side based on the energy balance.
- The condensation (T_H) and evaporation (T_L) temperatures are determined based on 151.68 kPa and 1,620.26 kPa pressure values, which are obtained from the real data.
- The values for \( \tau, i, j \) and \( n \) are 1500 h, 0.0125, 0.03 and 10 years, respectively.
- The unit cost of electricity is 0.1009 €/kWh.

4. Results and discussion

The values of each cycle state were determined within the scope of energy and exergy analysis based on the real data while the results are presented in table 2. As can be seen from the table, the exergy rates were obtained to be smaller than the corresponding energy rates for both the refrigerant and air sides. This shows the reference state contribution and the effect on energetic and exergetic analyses. Moreover, enthalpy and entropy variations against the temperature and pressure fluctuations indicate the similar behaviour for the two different types of fluids. When these values were substituted into the equations given in table 1, the energetic and exergetic parameters could be evaluated, namely the energy efficiency, the energy loss rate, the exergy efficiency and the exergy destruction rate, respectively. Within this scope, inlet - outlet energy rates and exergetic fuel-product rates were calculated for the main components. The former ones were evaluated as 67.20 kW – 64.79 kW, 2,470.04 kW – 2,417.64 kW, 38.81 kW (the same for inlet and outlet) and 1,606.00 kW – 1,643.99 kW for the compressor, the condenser unit, the expansion valve and the evaporator unit, respectively. These values led to an energy efficiency of 0.76 for the compressor. On the other hand, the latter ones were determined to be 10.02 kW – 6.32 kW, 1.65 kW – 1.50 kW, 5.39 kW – 4.28 kW and 3.35 kW – 2.98 kW for the compressor, the condenser unit, the expansion valve and the evaporator unit, respectively. As a result of these calculations, while the exergetic efficiency values were found as 0.63, 0.91, 0.79 and 0.89, respectively for the same sequence, the corresponding exergy destruction rates were determined to be 3.70 kW, 0.15 kW, 1.12 kW and 0.37 kW, respectively.
As can be seen in equation (17), the thermoeconomic analysis can be carried out under the condition that finding exergy destruction rates, hourly-levelised total equipment cost and hourly levelised destruction cost of the kth component. In this regard, the exergy destruction rates of the compressor, the condenser unit, the expansion valve and the evaporator unit were calculated to be 3.70 kW, 0.15 kW, 1.12 kW and 0.37 kW, respectively as given above. In addition, the total levelised costs of equipment was also obtained to be 0.1283 €/h, 0.04903 €/h, 0.01648 €/h and 0.05654 €/h, respectively based on the same sequence using equations (10) – (16). After that, one may perform thermoeconomic performance based on exergoeconomic factor and relative cost difference as given in equation (17), respectively. Table 3 illustrates the basic results based on the main components used within the MAC unit. As can be seen from the table, while the exergoeconomic factor is determined to be maximum at the condenser unit with a rate of 0.63, being a minimum value of 0.05 at the expansion valve. While the lower value for this factor shows that a technological improvement is needed, the higher value indicates that there is an opportunity for choosing a cheaper component although it causes an inefficiency. Furthermore, the reference cost difference is determined to be maximum 5.29 for the compressor and minimum 0.13 for the condenser unit.

Table 3. SPECO analysis results

| Component       | \( \dot{E}_{\text{des}} (\text{kW}) \) | \( \dot{E}_{\text{in}} (\text{kW}) \) | \( \dot{Z}_{\text{h}}^T (\text{€/h}) \) | \( c_{\text{i}} (\text{€/kWh}) \) | \( f_{\text{h}} (-) \) | \( r_{\text{h}} (-) \) |
|-----------------|----------------------------------------|-----------------------------------|--------------------------------------|------------------------------|----------------|----------------|
| Compressor      | 3.70                                   | 0.89                              | 0.12                                 | 0.26                         | 0.25           | 5.29           |
| Condenser       | 0.15                                   | 7.21                              | 0.04                                 | 0.19                         | 0.63           | 0.13           |
| Expansion valve | 1.12                                   | 7.05                              | 0.01                                 | 0.19                         | 0.05           | 0.33           |
| Evaporator      | 0.37                                   | 5.39                              | 0.05                                 | 0.25                         | 0.36           | 0.20           |

5. Conclusions
In this study, the three interrelated methods were applied to the considered system in the cooling mode through the energy and exergy efficiencies as well as thermoeconomic evaluation. Within the framework of these analyses, the main concluding remarks can be listed as follows:

- The energy efficiency of the compressor is calculated to be 0.76.
The exergy efficiencies of the main components are determined to be 0.63, 0.91, 0.79 and 0.89 for the compressor, the condenser unit, the expansion valve and the evaporator unit, respectively.

The hourly levelized total cost rates of the main components are obtained between 0.01 €/h and 0.12 €/h.

While the compressor has to be regarded as a primary component based on the exergetic evaluation, it states at the second stage after the expansion valve considering the thermoeconomic method.

The relative cost difference (non-exergy related and exergy related costs) illustrates that the condenser unit operates at more optimal condition among other components.

For the future study, advance exergoeconomic and exergoenvironmental evaluations may be applied to the considered system for understanding the interactions between each component and technological limits of them in terms of exergy destruction, cost and environmental impact.

**Nomenclature**

- \( \dot{C} \): cost rate of exergy streams (€/h)
- \( \dot{CA} \): annual capital cost rate (€/h)
- \( \dot{E} \): energy rate (W)
- \( \dot{Ex} \): exergy rate (W)
- \( PW \): present worth rate (€/h)
- \( S \): salvage value rate (€/h)
- \( W \): electrical work (W)
- \( \dot{Z} \): hourly levelized total cost rate (€/h)
- \( \dot{m} \): mass flow rate (kg/s)
- \( c \): cost per unit exergy (€/GJ)
- \( CRF \): capital recovery factor (-)
- \( ex \): specific exergy (kJ/kg)
- \( h \): specific enthalpy (kJ/kg)
- \( i \): interest rate (%)
- \( j \): salvage value ratio (-)
- \( n \): life time (years)
- \( P \): pressure (kPa)
- \( PWF \): present worth factor (-)
- \( s \): specific entropy (kJ/kgK)
- \( T \): temperature (°C)

**Subscripts**

- 0: dead state
- a: air
- act: actual
- comp: compressor
- cond: condenser
- des: destruction
- evap: evaporator
- MAC: mobile air conditioning
- OM: operation and maintenance
- Ref: reference state
- SPECO: specific exergy costing

**Superscripts**

- CI: capital investment
- OM: operation and maintenance
- T: total

**Greek letters**

- \( \eta \): energetic efficiency (-)
- \( \rho \): density (kg/m³)
- \( \tau \): annual number of operation hours (h/year)
- \( \psi \): exergetic efficiency (-)

**Abbreviations**

- AC: air conditioning.
- comp: compressor
- cond: condenser
- expv: expansion valve
- evap: evaporator
- MAC: mobile air conditioning.
- OM: operation and maintenance.
- Ref: reference state
- SPECO: specific exergy costing.
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