Exergy and energy analysis of a vapour compression refrigeration system for the investigation of a new refrigerant to be used on board the ships

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Abstract. This paper investigates the comparison between single stage vapour compression refrigeration cycles working with R134a - a traditional refrigerant for marine applications, and R435A - a new refrigerant having Dimethyleter (DME) 80% and R152a 20%. Since R134a shows a high GWP (Global Warming Potential), in the next future this refrigerant will be a subject for replacement. The new refrigerant taken into discussion here, R435A, shows a much lower GWP (3 compared with 1300 of R134a). The study allows the investigation of the performance of the cycles working with these two refrigerants, within a thermodynamic analysis, based on both first and second laws of thermodynamics. This kind of research is a strong tool used in design, optimisation and performance assessment of refrigeration systems. In the present paper are analysed the influence of evaporation temperatures on first and second law efficiencies and on exergy losses in the system. The results are obtained when this temperature varies in the range (248÷278) K. These results reveal the fact that R435A is a viable solution for R134a replacement, since average COP for R435A is about 35% higher than for R134a, the average exergy loss is around 40% smaller and the average exergy efficiency is approximately 35% higher.

1. Introduction
Nowadays, artificial cooling is an essential part of our lives, refrigeration, air conditioning and many other applications being technologies in continuous development. Food transport in cold spaces on board of ships is tightly bound with the constant demand increase [1,2].

Marine refrigeration enables safe food transport on long distances, by avoiding the spoiling during voyage, due to the slowing down of germs growth [3]. The dominant technology, when talking about marine refrigeration, is vapour compression. In the modern energy context, it is important to point out the fact that vapour compression refrigeration systems consume high-energy amounts, their optimization being an important task [4].

Sein the “quality” of high energy consumer of these type of plants, the issue of improving their energy efficiency, taking into consideration aspects such as efficient and environment friendly refrigerants (new refrigerants) and exergetic analysis, is of major concern [5].

Lately, HCFCs (Hydrochlorofluorocarbons) were commonly used in vapour compression systems, especially R22, having in view their very good thermodynamic and transportation features. Because of their negative impact on the ozone layer and contribution to the greenhouse effect, HCFCs are progressively taken out of use, at international level. In this context, HFCs (hydrofluorocarbons) are,
now, an accepted option, but their important global warming potential makes them to be candidates for replacement with eco-friendly refrigerants [6-8].

One of the most important HCF refrigerant, found in the list of marine refrigerants is R134a. Present concerns are focused on the substitution of this commonly used refrigerant with less greenhouse contributor ones. R152a shows similar properties with the ones of R134a and a lower GWP (Global Warming Potential).

Because of its flammability, it is recommended to be used in mixtures [9]. On the other hand, DME (dimethyleter) is a natural refrigerant, frequently used in the past, but abandoned because its safety aspects; nowadays DME is again in the attention of specialists due to its energetic and environmental behaviour [10].

The inconvenient coming from its flammability and explosion risks can be exceeded throughout some measures such as: enclose operations, ensuring local exhaust ventilation in the location of leakage, the use of special equipment, etc.

The actual refrigeration cycle is characterized by irreversibilities – which are reflected in the performance decrease. The limitation of the analysis based only on the first law of the thermodynamics which considers only the energy conservation aspect, leads to the need of the exergy analysis, in order to assess accurately the performance and to identify losses [11].

In this respect, a viable thermodynamic analysis of the vapour compression cycle implies both calculations of Coefficient of Performance (or first law efficiency) and exergy efficiency (or second law efficiency).

In the light of the above mentioned, this paper deals with the theoretical investigation of the new R435A (DME 80% / R152a 20%) as a substitute of R134a, within a thermodynamic performance analysis of a standard vapour compression cycle, based on both laws of thermodynamics.

In this study are investigated Coefficient of Performance, exergy loss and exergy efficiency of R134a and R435A, in order to optimize the considered system.

2. Methods and materials

The focus on these refrigerants is based on their thermo-physical and environmental properties, given in table 1 [12-14]. It is considered a subcooled and superheated vapour compression refrigeration cycle, its (T-s) diagram being provided in figure 1.

| Table 1. Thermo-physical and environmental properties. |
|-------------------------------------------------------|
| Property | R134a | R152a | DME |
| Molecular mass (kg/kmole) | 102.3 | 66 | 46.07 |
| Triple temperature (°C) | –103.3 | –118.6 | –141.5 |
| NBP (Normal Boiling Point) (°C) | –26 | –24 | –24.8 |
| Critical temperature (°C) | 101.06 | 113.6 | 127.2 |
| Critical pressure (MPa) | 4.06 | 4.5 | 5.34 |
| Critical density (kg/m³) | 511.9 | 368 | 271 |
| Miscibility with oil | Nil | 120 | 10 |
| ODP (Ozone Depletion Potential) | 0 | 0 | 0 |
| GWP (Global Warming Potential) | 1300 | 120 | 3 |
Figure 1. Thermodynamic cycle in T-s diagram of the considered refrigeration system.

The analysis developed based on the following:

- in all the system’s components are kept steady state conditions
- pressure drops in suction line and discharge line are neglected
- heat exchange between the system and the environment is neglected
- kinetic and potential energy and exergy losses are neglected
- cooling capacity: 1 kW
- evaporation temperature: (248÷278) K
- condensation temperature: 316 K
- subcooling and superheating degrees: 288 K
- average ambient temperature: 298 K
- compressor efficiencies: 0.75
- electric motor efficiency: 0.8

Exergy analysis is based not only on the first law of thermodynamics, as in the case of energy analysis, it is based on the first and second laws of thermodynamics. In this respect, the exergy analysis is able to provide information on how, location and the performance decreases, since irreversibilities lead to performance degradation.

This analysis is developed on the theoretical formulation, given below [15].

The specific exergy:

\[ ex = (h - h_0) - T_0 (s - s_0) \]  

where:
- \( h \) – specific enthalpy (kJ/kg)
- \( s \) – specific entropy (kJ/kgK)
- \( T_0 \) – surrounding ambient temperature (K)
- \( h_0 \) and \( s_0 \) – enthalpy and entropy at the surrounding conditions

For the four main components of the system:

- in the evaporator, the heat load (\( Q_{ev} \)) and the exergy loss (\( E_{x_{Dev}} \)):

\[ Q_{ev} = m_f \left( h_1 - h_4 \right) \]  

\[ E_{x_{Dev}} = m_f \left[ (h_4 - h_1) - T_0 (s_4 - s_1) \right] + Q_{ev} \left( 1 - T_0 / T_{ev} \right) \]

where:
- \( m_f \) – refrigerant mass flow (kg/s)
h₁ and s₁ – enthalpy and entropy at the evaporator exit
h₄ and s₄ – enthalpy and entropy at the evaporator inlet
Tₑv – absolute evaporation temperature (K)

• in the compressor, the work input (W₀p) and the exergy loss (ExDcp):

\[ W₀p = \dot{m}_f \left( h_2 - h_1 \right) \]  \hspace{1cm} (4)

where: h₂ – enthalpy at the compressor exit

\[ ExDcp = \dot{m}_f \left[ (h_1 - h_2) - T₀ \left( s_1 - s_2 \right) \right] + W₀el \]  \hspace{1cm} (5)

where: W₀el – electrical power (kW)
s₂ – entropy at the compressor exit

\[ W₀el = \frac{W₀p}{\eta_m \cdot \eta_{el}} \]  \hspace{1cm} (6)

where: ηₘ / ηₑ – mechanical / electrical efficiency

• in the condenser, the heat load (Q₀cd) and the exergy loss (ExDcd):

\[ Q₀cd = \dot{m}_f \left( h_3 - h_2 \right) \]  \hspace{1cm} (7)

where: h₃ – enthalpy at the condenser exit

\[ ExDcd = \dot{m}_f \left[ (h_2 - h_3) - T₀ \left( s_2 - s_3 \right) \right] - Q₀cd \left( 1 - T₀ / T₀ \right) \]  \hspace{1cm} (8)

where: T₀ – absolute condensation temperature (K)
s₃ – entropy at the condenser exit, (h₃ being explained above)

• in the throttling valve, since the process is isenthalpic, the exergy loss (ExDTV):

\[ ExDTV = \dot{m}_f \left( s_3 - s_4 \right) \]  \hspace{1cm} (9)

• The Coefficient of Performance, also known as the first law efficiency:

\[ COP = \frac{Q₀ev}{W₀el} \]  \hspace{1cm} (10)

• The overall exergy loss:

\[ ExDTOT = ExDev + ExDcp + ExDcd + ExDTV \]  \hspace{1cm} (11)

• The exergy efficiency, also known as the second law efficiency:

\[ \eta_{ex} = \frac{Ex₁ - Ex₄}{W₀el} \]  \hspace{1cm} (12)

3. Results and discussions
The following results are obtained in base of the above given equations, for the cycle working with the actual refrigerant (R134a) and the one working with the new refrigerant (R435A). The software EES (Engineering Equation Solver) has been used for the simulation. The comparison of the results are provided in the following figures.

Figure 2 shows the influence of the evaporation temperature increase on the Coefficient of Performance (COP) values; this important efficiency criteria provides information related to the amount of electrical power input to produce a specific amount of cold.
From figure 2 results that the increase of the evaporation temperature has a beneficial effect on COP, for the both cycles.

This is explained by the fact that for higher evaporation temperatures are obtained increased refrigerating effect in the cycles. The best COP values are seen for the cycle working with new refrigerant (R435A). The average COP for R435A is about 35% higher than R134a.

Figure 3 shows the influence of evaporation temperature increase on the exergy loss.

Figure 3 reveals the fact that the increase of the evaporation temperature leads to a decrement of exergy losses, the trend being the same for the both refrigerants.

This result is explained by the fact that at higher evaporation temperatures, the heat transfer in the evaporator is more intense, thus, the refrigerating effect is improved, so exergy losses are diminished.
The less exergy losses are observed for the cycle working with R435A. The average exergy loss for R435A is around 40% smaller than R134a.

From figure 4 can be seen what happens with exergy efficiency values, when the evaporation temperature increases.

![Figure 4: (\(\eta_{ex} - T_{ev}\)) dependency.](image)

The exergy efficiency decrease together with increase of the evaporation temperature. This result is explained by the Coefficient of Performance increase with increment of this temperature. This situation causes minimum exergy intake to accomplish the given task. This trend in available for the both refrigerants considered. The cycle working with R435A shows the better second law efficiency. The average second law efficiency increase is about 35%, when using R435A in the cycle.

4. Conclusions
A comparative analysis of the performance of a single stage vapour compression refrigeration cycle working with R134a and R435A was developed.

The influence of the evaporation temperature increase on the Coefficient of Performance (first law efficiency), exergy loss and exergy efficiency (second law efficiency) was studied in the context of environmental concern and energy efficiency need.

The evaporation temperature varied in the range (248÷278) K, the condensation temperature was kept constant (316 K) and the average ambient temperature was 298 K. The cycle includes sub cooling and superheating processes.

It was observed that:
- the increase of evaporation temperature leads to an increase of the first law efficiency, in both cases; this efficiency is about 35% higher when the working refrigerant is R435A,
- the increase of the evaporation temperature leads to a decrease of the exergy loss, in both cases; this loss is lower when the working refrigerant is R435A (about 40% less),
- the increase of the evaporation temperature leads to a decrease of the second law efficiency, in both cases; the exergy efficiency is higher when the working refrigerant is R435A (about 35% higher).

The analysis highlights the fact that the study based only on the first law of thermodynamics is not reliable, a consistent research requiring concepts belonging to the both laws.
The results show that R435A is a strong candidate for the replacement of R134a, with the implementation of specific measure – in order to ensure safety on board.

5. References
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