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Energy and exergy analysis of the heat pump cycle using working fluids with low environmental impact

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***Abstract*— This study presents the energetic and energetic analysis of the heat pump cycle, used for heating residential spaces. The heat pump is of the air-water type, taking heat at the level of the evaporator from the environment. The working fluids used are: R1233zd(E), R1234ze, R152a, R1234yf. Exergy analysis is used as a research tool. Based on the exergy analysis, the identification of malfunctions at the level of each device and process can be easily achieved. The study shows that the working fluid R1233zd(E) presents the highest coefficient of performance and the highest exergetic efficiency.**

Keywords—energy, exergy analysis, heat pump, ecological working fluids

I. INTRODUCTION

Nowadays, scientific development offers many solutions for ensuring thermal comfort in residential spaces, but the most common equipment to satisfy this need is equipment based on the combustion of methane gas.

Due to the policy of reducing greenhouse gases released into the atmosphere, the European Union adopts a series of objectives and regulations aimed at reducing the consumption of primary energy and implicitly reducing emissions.

On 28 November 2018 [1] the European Commission presented its long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. This is based on a new energy policy framework established within the "Clean Energy for All Europeans" package which aims to limit the increase in global temperature below 2 0 C or 1.5 0C until the year 2050.

In December 2019 [2], the European Commission launched the "European Green Deal" project, which sets out measures that will transform Europe into the first climate neutral continent by 2050.

Glasgow conference from October - November 2021 [3] decided to reduce emissions to limit global warming by phasing out coal-based energy, stopping deforestation, accelerating the transition to electric vehicles and reducing emissions.

These goals will be successful if heating based on heat pump solutions is included. This equipment does not induce any other carbon emission, other than the one produced at the power plant. If we take into account the fact that most of the electricity is produced from renewable sources such as solar, wind or hydro, the positive effect of using heat pumps on the reduction of greenhouse gas emissions can be quantified.

Due to the advantages of these equipment, heat pumps systems are intensively studied subject. Sho F et al. [4] perform a theoretical analysis on low global warming potential fluids R1234ze(E) and R1234ze(Z). The purpose of the research is to investigate the performance of the working fluids at condensation temperatures above 75°C. The comparative analysis demonstrates that the working fluids R1234ze(E) and R1234ze(Z) can successfully replace the R134a. Evaluations have shown that the working fluid R1234ze(Z) is more suitable for applications where the condensation temperature exceeds 100°C.

Alptung Y et al. [5] carried out a theoretical analysis focused on the replacement of R134a working fluids in existing heat pump systems with mechanical vapor compression. Environmentally friendly working fluids to replace R134a are R1234yf and R1234ze. The exergy analysis indicates that the refrigerant R1234ze has similar performances to the working fluid R134a.

Carlos R et al [6] performs a theoretical analysis focused on the replacement of R245fa working fluids with R1224yd(Z) working fluid in high-temperature heat pump applications, using as a heat source, hot water from industrial processes at temperatures above 80°C. The simulation was performed for condensation temperatures between 110-140°C. The results demonstrate that R1224yd(Z) working fluid can successfully replace R245fa, but the performance coefficient of R1224yd(Z) is positioned below the performance coefficient of the R245fa refrigerant regardless of the condensation temperature.

Carlos R et al. [7] performs a comparative analysis focused to replacement of R134a working fluids with R515B and R1234ze(E) working fluids. In order to protect the compressor but also to reduce exergy destruction at the level of the throttling process, a compression cycle in one step with an internal regenerative heat exchanger is chosen. The study shows that the working fluids R515B and E1234ze(E) can replace R134a working fluids, but offer a heating capacity approximately 25% lower than R134a working fluids due to differences in thermophysical properties.

In engineering practice, the structural and functional optimization of heat pump equipment is based on energy analysis, analysis that uses the first law of thermodynamics, respectively the analysis of the cycles through the perspective of the energy balance. Table 1 shows the properties and ecological characteristics of the working fluids investigated in this study.

TABLE I. CHARACTERISTIC PROPERTIES OF THE INVESTIGATED WORK FLUIDS [8-12]

Working fluids	Chemical formula	GWP	Critical temperature [°C]	Critical pressure [bar]
R1234ze	C3H2F4	7	109.4	36.4
R152A	C2H4F2	124	113.26	45.20
R1234yf	C3F4H2	4	94.71	33.82
R1233zd(E)	C3CF3H2	1	220.45	36.23

A thermodynamic investigation based only on the first law of thermodynamics did not provide a real picture when the boundary of the system is penetrated by several forms of energy, as in the case of heat pumps where the system interacts through both heat exchange and mechanical work.

Exergy analysis can qualitatively investigate the forms of energy interacting with the system. Based on the exergy analysis, the identification of exergy dissipative areas can be done easily [13-18]. In this paper, in order to complete the researche undertaken in the previously presented works, an exergetic analysis is used as a research tool to investigate the performance of four work fluids with a low impact on the environment: R1233zd(E), R1234ze, R152a and R1234yf respectively.

II. DESCRIPTION OF THE HEAT PUMP SYSTEM

Figure 1 (a) shows the schematic mechanical the vapor compression heat pump. This equipment forms a closed cycle where the working fluid undergoes transformations of vaporization, compression, condensation and throttling. Figure 1 (b) shows the operating cycle of the mechanical vapor compression heat pump in a compression stage in the temperature-entropy (t-s) diagram.

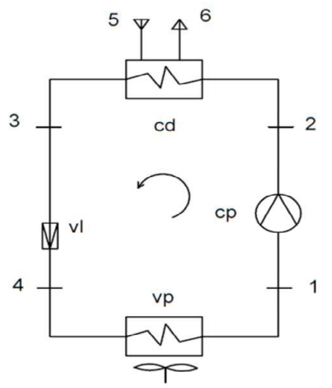

Fig. 1. (a) diagram of the heat pump compression stage.

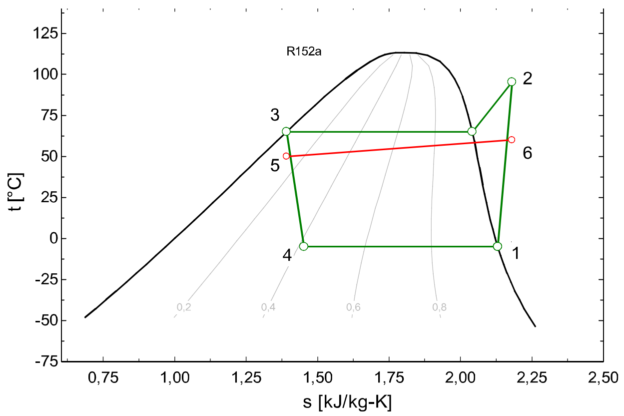

Fig. 1. (b) heat pump cycle in t-s diagram

TABLE II. MAIN THERMODYNAMIC PARAMETERS

Description	Value
Heated water temperature at the inlet, t_5[°C]	50
Heated water temperature at the outlet, t_6[°C]	60
Ambient temperature, t_0[°C]	0
Evaporation temperature, t_{vp}[°C], with $t_{vp} = t_0 - \Delta t_p$	-5
Condensation temperature, t_{cd}[°C], with $t_{cd} = t_6 + \Delta t_p$	65
Minimum temperature difference in heat exchangers (at pinch point), Δt_p[°C]	5

The product delivered by the equipment is heated water, from the state of water entry (5) to the state of water exit (6), specified in the t-s diagram. The simulation of the operation of the equipment shown in figure 1, was performed based on the software Engineering Equation Solver [19].

The main thermodynamic parameters and state variables that are used to determine the characteristics and performance of the equipment are presented in Table 2.

III. MATHEMATICAL MODELING

For 1 kW of heat rejected at the level of the condenser ($\dot{Q}_{cd}$), the refrigerant flow rate circulated by the cycle can be determined:

$$\dot{m} = \frac{\dot{Q}_{cd}}{h_2 - h_3} \quad (1)$$

The mechanical work consumed by the heat pump compressor is:

$$\dot{W} = \dot{m}(h_2 - h_1) \quad (2)$$

The heat flow taken at the level of the evaporator.

$$\dot{Q}_{vp} = \dot{m}(h_1 - h_4) \quad (3)$$

The energy balance of the equipment shown in figure 1.

$$\dot{Q}_{vp} + \dot{W} = \dot{Q}_{cd} \quad (4)$$

To identify every failure in each process and device that compose the equipment an exergetic analysis is used.
Exergy balance equation for a closed system [20-22]:

$$\sum \dot{Ex}_Q = \sum \dot{W} + \sum \dot{I} \quad (5)$$

Equation (5) applied to the equipment described in figure 1 becomes:

$$\dot{Ex}_Q^{T_{vp}} + \dot{Ex}_Q^{T_{cd}} = \dot{W} + \dot{I}_{cp} + \dot{I}_{vl} \quad (6)$$

Considering the sign of each form of energy interacting with the system and taking into account the exergy losses associated with heat transfer from the evaporator and condenser, equation (6) can be written:

$$|\dot{W}| = |\dot{Ex}_Q^{T_{5-6}}| + \dot{I}_{\Delta t,vp} + \dot{I}_{cp} + \dot{I}_{\Delta t,cd} + \dot{I}_{vl} \quad (7)$$

The energy performance coefficient is:

$$COP = \frac{\dot{Q}_{cd}}{\dot{W}} \quad (8)$$

The exergetic efficiency can be calculated by using the expression:

$$\eta_{ex} = \frac{\dot{Ex}_Q^{T_{5-6}}}{\dot{W}} \quad (9)$$

Exergy destruction coefficient is defined as the ratio between exergy destruction to total energy intake:

$$\psi_i = \frac{I_i}{W} \cdot 100 \quad (10)$$

IV. RESULTS AND DISCUSSIONS

The simulation and determination of the energy and exergy analysis results were determined based on the Enginering Equation Solver software.

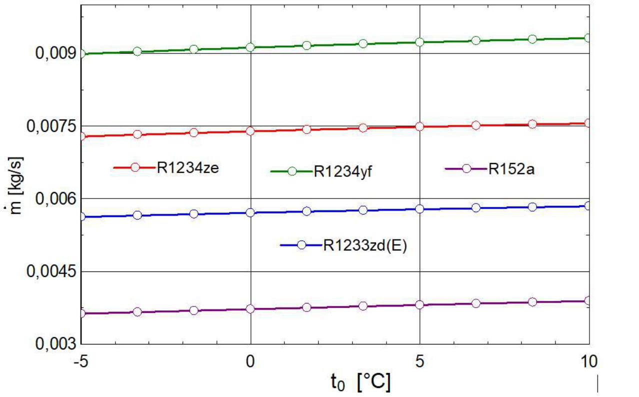

Fig. 2. Mass flow rates of working fluid at the ambient temperature variation, t_0[°C]

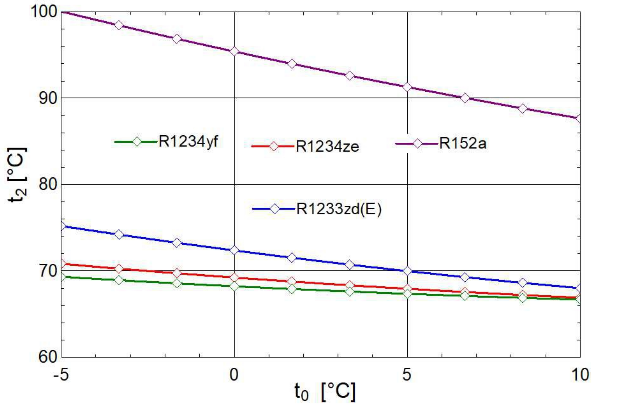

Fig. 3. Compressor discharge temperature at ambient temperature variation, t_0[°C]

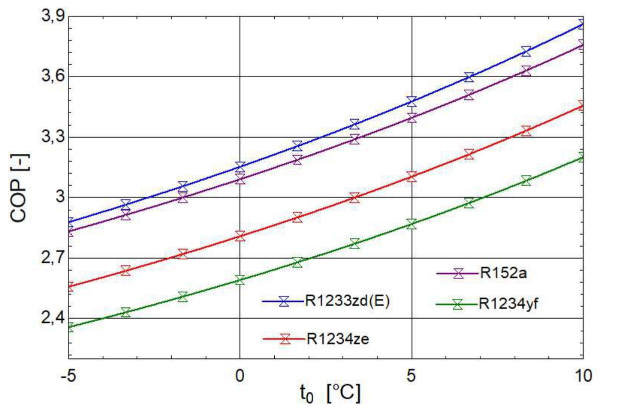

Fig. 4. Performance coefficient at ambient temperature variation, t_0[°C]

To evaluate the performance and identify the characteristics of the 4 working fluids used, the temperature t0 was considered as parameter.

Figure 2 shows the mass flow rates of working fluid circulated by the heat pump cycle for 1 kW of heat rejected at the condenser level.

Following the diagram shown in figure 2, the working fluid R152a presents the lowest flow rate, which is an important characteristic from the point of view of the initial investment, while the working fluid R1234yf presents the highest flow rate.

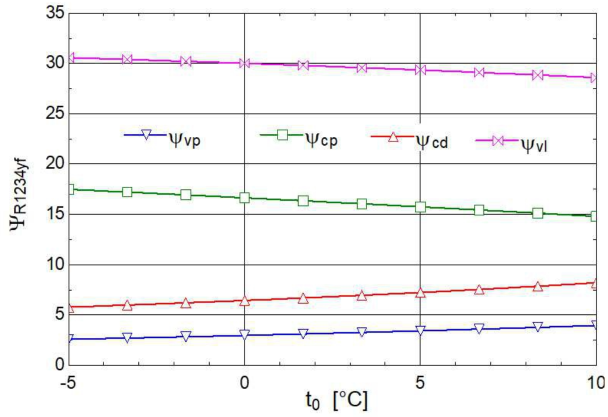

Fig. 5. The exergy destructions associated with each device and process in case of the working fluid R1234yf at the variation of the ambient temperature, t_0[°C]

The discharge temperature (Figure 3) from the compressor represents an important characteristic both constructively and functionally. A high discharge temperature above 130ºC, leads to defective lubrication of the moving parts of the compressor.

The performance coefficient represents the amount of heat rejected at the condenser level (energy product) related to the mechanical work consumed by the heat pump compressor. According to figure 4 the working fluid R1233zd(E) presents the highest coefficient of performance while the working fluid R1234yf the lowest coefficient of performance.

The exergy destructions associated with each device and process in case of the working fluid R1234yf (Figure 5) at the variation of the ambient temperature, t_0[°C]

From a functional point of view, a high discharge temperature leads to a large exergy destruction at the condenser level, following figures (7-9) show the case of the working fluid R152a, the exergy destruction in the condenser presents the highest value while the working fluid R1233zd(E) presents the lowest exergy destruction.

Due to its strong irreversible character, the throttling process represents the main exergy destruction for the 4 investigated fluids. The working fluid R1234yf shows the highest exergy destruction in the throttling process.

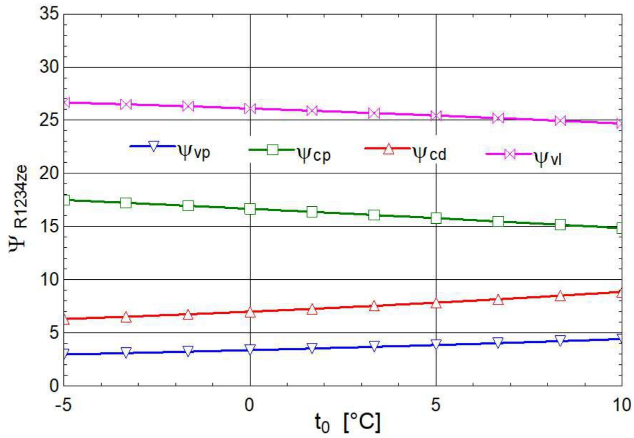

Fig. 6. The exergy destructions associated with each device and process in case of the working fluid R1234ze at the variation of the ambient temperature, t_0[°C]

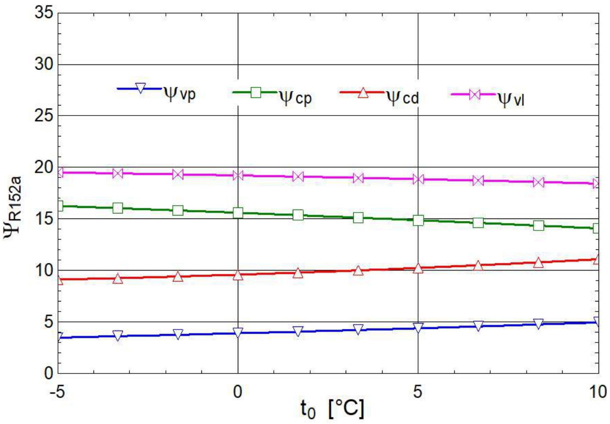

Fig. 7. The exergy destructions associated with each device and process in case of the working fluid R152a at the variation of the ambient temperature, t_0[°C]

Exergy destruction from the compression process also shows high values. Following the figures (5-8) show that in the case of the 4 investigated working fluids the values of exergy destruction in the compression process are close.

Following the exergy destructions associated with heat transfer in the condenser and evaporator, their values have acceptable values.

The working fluids R152a and R1233zd(E) present the highest exergetic efficiency. This is due to the lower exergy destruction in the throttling process compared to the other investigated working fluids. The lower exergy destruction at the condenser level makes the difference between the two fluids (R152a and R1233zd(E)) and places the working fluid R1233zd(E) with the highest exergetic performance coefficient.

Following the results of the exergy analysis that indicates the location of each malfunction, processes with the highest exergy destruction can be prioritized.

In this case, the throttling and compression processes are prioritized in order to optimize the structure.

The study presents the performance of the heat pump cycle using working fluids with a low impact on the environment.

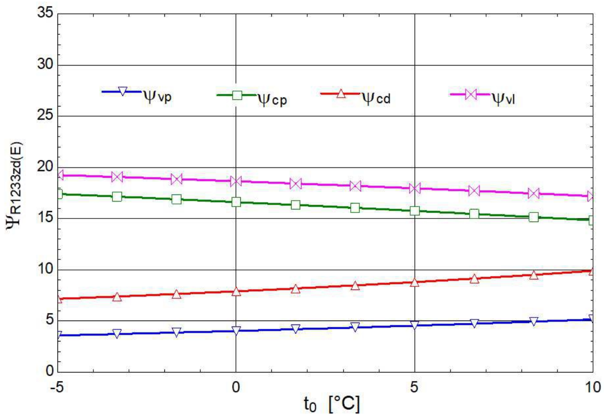

Fig. 8. The exergy destructions associated with each device and process in case of the working fluid R1233zd(E) l at the ambient temperature variation, t_0[°C]

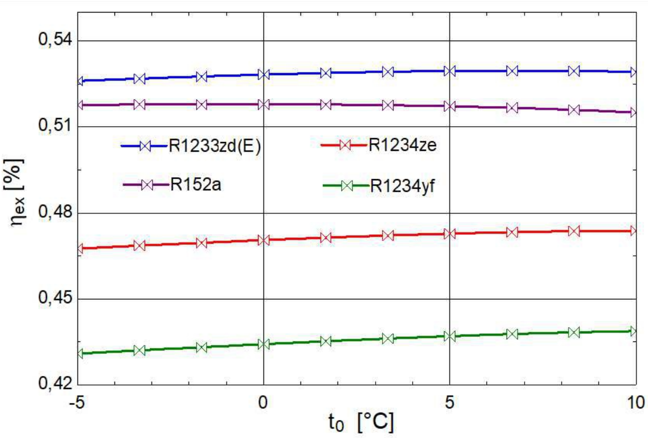

Fig. 9. Exergetic efficiency for the 4 investigated working fluids (R1233zd(E), R1234ze, R152a, R1234yf.)

Energy destruction in the throttling process can be reduced by applying regenerative subcooling.

V. Conclusions

The energetic and exergetic performances of the working fluids (R1233zd(E), R1234ze, R152a, R1234yf) were investigated.

The working fluid R152a presents the lowest mass flow rate of the cycle, an important characteristic from the point of view of the initial investment of the equipment.

Based on the exergetic analysis, it was possible to investigate the four working fluids (R1233zd(E), R1234ze, R152a, R1234yf) and identify the processes and devices that present a dissipative character.

In the case of the four fluids presented, the throttling process presents the highest exergy destruction followed by the compression process.

The working fluid R1233zd(E) presents the highest coefficient of performance and the highest exergetic efficiency associated with the lowest exergy destruction in the throttling process.

Exergy analysis is a powerful optimization tool that makes it possible to investigate each component. Based on it, the optimization of the heat pump cycles can be easily done.

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