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Advanced exergy analysis of heat pumps with different eco-friendly working fluids

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Abstract

The advanced exergy method provides engineers with the best information with respect to options for improving the overall thermodynamic efficiency of an energy conversion system.

This paper presents the results of the advanced exergy analysis of an air source heat pump to perform a comparison involving different working fluids, i.e.R410A, R134a and some of their eco-friendlier replacements (R600a, R290, R1270, R1234ze(E)), assuming the same heat demand for the condenser and the same low temperatures for the air. It was found that the biggest exergy destruction belongs to the thermodynamic cycle with R410A. In case of applying a R410A cycle with only unavoidable irreversibilities, the total exergy destruction could be decreased by 47%. Compared to R410A additional decrease of the total exergy destruction could be obtained in case of only unavoidable irreversibilities for R600a (14.6%), R1270 (8.5%), R290 (8.5%) and R1234ze (7.9%). This reduction was found to be 10.4% for R134a. The biggest share of avoidable exergy destruction in the investigated heat pumps could be removed by reducing the irreversibilities within the evaporator. Taking into account technological limitations, in case of removing all the avoidable irreversibilities within the evaporator 26% of the total exergy destruction could be decreased in the investigated heat pump with R410A. In addition, in comparison with the R410A cycle, additional decrease of the total exergy destruction could be obtained in case of reducing irreversibilities within only the evaporator and replacing R410A with R600a (13.1%), R1270 (7.9%), R290 (7.5%) and R1234ze(E) (7.5%). This reduction was found to be 9.6% for R134a. Therefore, it could be concluded that today's most powerful thermodynamic tool, i.e. the advanced exergy analysis, suggests the adoption of hydrocarbons in air-source heat pump units over R1234ze(E) as replacements of currently used working fluids (i.e. R410A and R134a).

1 Introduction

Heat pump systems are key solutions to mitigate climate change significantly. In order to achieve such a target, the implementation of highly thermodynamically efficient heat pumps relying on very low global warming potential (GWP) refrigerants is compulsory. In case of choosing refrigerants for heat pump applications many criteria need to be met simultaneously (e.g. suitable thermodynamic properties, stability in the system, no ozone depletion potential, very low GWP). Most of current heat pumps use hydrofluorocarbons, i.e. R410A and R134a, which have lower environmental impact compared to chlorofluorocarbons and hydrochlorofluorocarbons. However, due to the massive GWP of R410A and R134a, in the last decade studies has been devoted to investigate environmentally friendlier alternatives, i.e. hydrofluoroolefins [1] and hydrocarbons [2]. Highly performing heat pumps can be implemented with the aid of exergy-based methods, being widely recognized as the most suitable methods to evaluate and improve the thermodynamic performance of any energy conversion system considerably [3-5]. The application of these tools provides the possibilities to reveal the location, the magnitude and the sources of thermodynamic inefficiencies, costs and environmental impact. However, the so called advanced exergy analysis [3-5] gives unique possibilities as compared to the conventional exergy method, as it can evaluate the detailed interactions among components of the overall system and the real potential for improving a system component.

In work **Błąd! Nie można odnaleźć źródła odwołania.** six refrigerants are selected including natural refrigerant (i.e. R718, R600, R601) and synthetic working fluids (i.e. R1234ze(Z), R1336mzz(Z), R245fa) to compare the performance of different high temperature heat pumps for industrial waste heat recovery. The experimental comparison showed that R718 is the most suitable refrigerant for the investigated application.

The aim of the study **Błąd! Nie można odnaleźć źródła odwołania.** was to investigate the theoretical performance of a vapour compression refrigeration system with R134a, R143a, R152a, R404A, R407C, R410A, R502 and R507A based on energy and exergy concepts. It was found that R134a has the highest performance and R407C refrigerant has poor performance. However, it is worth remarking that the use of R134a is bound to be abandoned soon due to its dramatic GWP.

In the paper **Błąd! Nie można odnaleźć źródła odwołania.**, energy and exergy analyses of R22 and its old alternatives, R407C and R410A, in a vapour compression refrigeration system were performed. From the point of view of the first and the second laws analysis and taking into account some properties, such as ozone depletion potential and global warming potential, it was concluded that R407C is a better alternative to R22 than R410A.

In [9] a thorough thermodynamic analysis of ground source heat pumps was presented. The results obtained suggested the adoption of R454B rather than R32 to substitute R410A in the selected application.

Padmanabhan et al. [10] experimentally investigated coefficient of performance (COP), irreversibilities and exergy efficiency of an air conditioning system using R22, R134a, R290 and R407C. It was found that R290 has the highest performance among all the evaluated refrigerants.

On the base of advanced exergy analysis Morosuk and Tsatsaronis [4] examined the performance of vapour compression refrigeration systems operating with four one-component working fluids (R125, R134a, R22 and R717) and two mixtures (R500 and R407C). However, the main target of this study was to prove the possibility to apply an advanced exergy analysis to a refrigeration unit.

De Paula et al. [11] compared the environmental, energy and exergy performance of R290, R1234yf, R744 with R134a in a steady-state model of a vapour compression refrigeration system. The results showed that R290 provides the best thermodynamic and environmental performance.

The work [12] presented the evolution of a concept of air-source heat pump for simultaneous heating and cooling. Two prototypes working with R407C and R290 were tested. The experimental results showed that the second solution has higher performance than the first one regarding exergy aspects.

From the literature review above, it is possible to conclude that most of the investigations on heat pump using low-GWP refrigerants is based on conventional thermodynamic assessments. However, no advanced exergy analyses, being the most powerful tool to evaluate and enhance the performance of any

energy conversion system, has been carried out to the best of the authors' knowledge. Therefore, the target of this study is to fill this knowledge gap by implementing the advanced exergy analysis of an air-source heat pump using ultra-low GWP working fluids (i.e. R600a, R290, R1270, R1234ze(E)) to determine the improvement potentials of its components along with their thermodynamic interactions. The results obtained were compared to those of today's most employed refrigerants in the air-source heat pump sector, i.e. R410A, R134a.

2 Methodology

According to the advanced exergy analysis, exergy destruction within each system component is split into endogenous/exogenous parts ($\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX}$), unavoidable/avoidable parts ($\dot{E}_{D,k} = \dot{E}_{D,k}^{AV} + \dot{E}_{D,k}^{UN}$) and combined according to the two approaches of splitting ($\dot{E}_{D,k} = \dot{E}_{D,k}^{EN,UN} + \dot{E}_{D,k}^{EX,UN} + \dot{E}_{D,k}^{EN,AV} + \dot{E}_{D,k}^{EX,AV}$) [3-5]. To split exergy destructions into the above-mentioned parts the thermodynamic-cycle-based approach was used [3, 4]. The product exergy of the heat pump in all analysed cycles remained unchanged.

The endogenous part of exergy destruction ($\dot{E}_{D,k}^{EN}$) of the k-th component is associated only with the irreversibilities occurring in the same component when all other components operate in an ideal way and the component being considered operates with its current efficiency. For calculating the endogenous part of the exergy destruction within each component of the heat pump the hybrid cycles with only one irreversible component is analysed. The exogenous part of exergy destruction ($\dot{E}_{D,k}^{EX}$) is caused within the k-th component by the irreversibilities that occur in the remaining components or the structure of the overall system and is calculated as the difference between total and endogenous exergy destruction [3-5].

Cycle with unavoidable exergy destructions ($\dot{E}_{D,k}^{UN}$) considers only unavoidable irreversibilities that cannot be further reduced even in the near future due to technological limitations, such as availability and manufacturing methods. To split the exergy destruction into unavoidable and avoidable parts a cycle in which only unavoidable exergy destruction (with unavoidable inefficiencies) occurring within each component has been created. The difference between total and unavoidable exergy destruction for a component is the avoidable exergy destruction ($\dot{E}_{D,k}^{AV}$) that should be considered during the improvement procedure [3-5].

In case of calculation of the additional parts of exergy destruction, only the value of the unavoidable endogenous exergy destruction ($\dot{E}_{D,k}^{UN,EN}$) needs to be obtained using the thermodynamic cycle-based approach [3, 4]. For this purpose the approach similar to one applied for calculating the endogenous part of the exergy destruction can be used. However, in this case the efficiency of each component is equal to the efficiency used to calculate its unavoidable exergy destruction [3-5].

The remaining parts of the exergy destruction are then calculated as follows [3, 4]

$$\dot{E}_{D,k}^{UN,EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN,EN} , \tag{1}$$

$$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN} , \tag{2}$$

$$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{AV} - \dot{E}_{D,k}^{AV,EN} . \tag{3}$$

For obtaining a deeper understanding of the interactions among components, the exogenous exergy destruction (as well as the exogenous unavoidable and the exogenous avoidable exergy destructions) within the k-th component should also be split [3]

$$\dot{E}_{D,k}^{EX} = \sum_{\substack{r=1 \\ r \neq k}}^{n-1} \dot{E}_{D,k}^{EX,r} + \dot{E}_{D,k}^{mexo} , \tag{4}$$

where $\dot{E}_{D,k}^{EX,r}$ represents part of the exogenous exergy destruction within the k-th component that is caused by the irreversibilities occurring within the r-th component, while $\dot{E}_{D,k}^{mexo}$ describes the mexogenous exergy destruction (from mixed exogenous exergy destruction) within the k-th component and is caused by the combined interactions of two or more components.

To identify the importance of the components from the thermodynamic viewpoint and priorities for improving the components, the investigator can use the sum of the avoidable endogenous exergy destruction within the k-th component $\dot{E}_{D,k}^{AV,EN}$ and of the avoidable exogenous exergy destructions within the remaining components caused by the k-th component $\sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,r}^{AV,EX,k}$ [4]

$$\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,r}^{AV,EX,k} \ . \tag{5}$$

From the viewpoint of practical application the avoidable parts of exergy destruction are the most interesting.

The analysis was performed for the air-source heat pump with 12 kW heating capacity [13]. The following parameter values were set: the low temperature heat source medium (outside air) was assumed to be cooled in the evaporator from -10 ºC down to -15 ºC [13]; water as the secondary working fluid in the condenser was assumed to be heated from 33ºC up to 43ºC [13]; the minimal temperature differences in the evaporator was 12 K [13] and in the condenser was equal to 5 K [13]. The calculated value of the real isentropic efficiency of the compressor in the nominal mode was equal to 0.7 [13]. For evaluating unavoidable exergy destructions the following parameter values were assumed: the unavoidable temperature differences in the evaporator and the condenser were equal to 3 K and 1 K, respectively [13]. The unavoidable compressor efficiency was equal to 0.88 [13]. For creating the theoretical cycle of the air-source heat pump the following assumptions were used: the minimal temperature differences in the evaporator and the condenser were equal to 0 K [13]; the efficiency of the working fluid compression was equal to 1 [13]; the throttling process was replaced by an ideal expansion process [4]. A set of nonlinear algebraic equations, involving heat, mass balances, heat transfer and equations for calculation of thermodynamic properties of working fluids, were utilized. CoolProp software [14] was employed for providing the thermophysical properties of the working fluids, while the simulation model of the heat pump was implemented in MathCad math environment [15]. The ambient (outdoor) temperature equal to -10 ºC was chosen as the reference state for the exergy analysis [16].

3 Results and discussion

Figure 1 illustrates values of the total exergy destruction for the investigated heat pump. The results obtained showed that the biggest exergy destruction (3.09 kW) belongs to the heat pump with R410A. Among the chosen working fluids the system with R600a has the lowest value of the total exergy destruction (2.79 kW). It could be observed that the main contributors to the exergy destruction of the heat pump are the compressor and the throttling valve. In addition, for the selected working fluids the values of exergy destruction for all these components and for the evaporator (1.03÷1.12kW for the compressor, 0.90÷1.03 kW for the throttling valve and 0.43÷0.45kW for the evaporator) are very close. The choice of the working fluid provided the highest decrease of exergy destruction within the condenser. As for the heat pump with R410A, the exergy destruction within the condenser was equal to 0.61 kW, whereas for the system using R1234ze(E) the exergy destruction of this component decreased to 0.36 kW, for R290 to 0.41 kW, for R1270 to 0.47 kW and for the R600a to 0.35 kW, respectively. As regards the other selected high-GWP refrigerant (i.e. R134a), this reduction was equal to 0.42 kW.

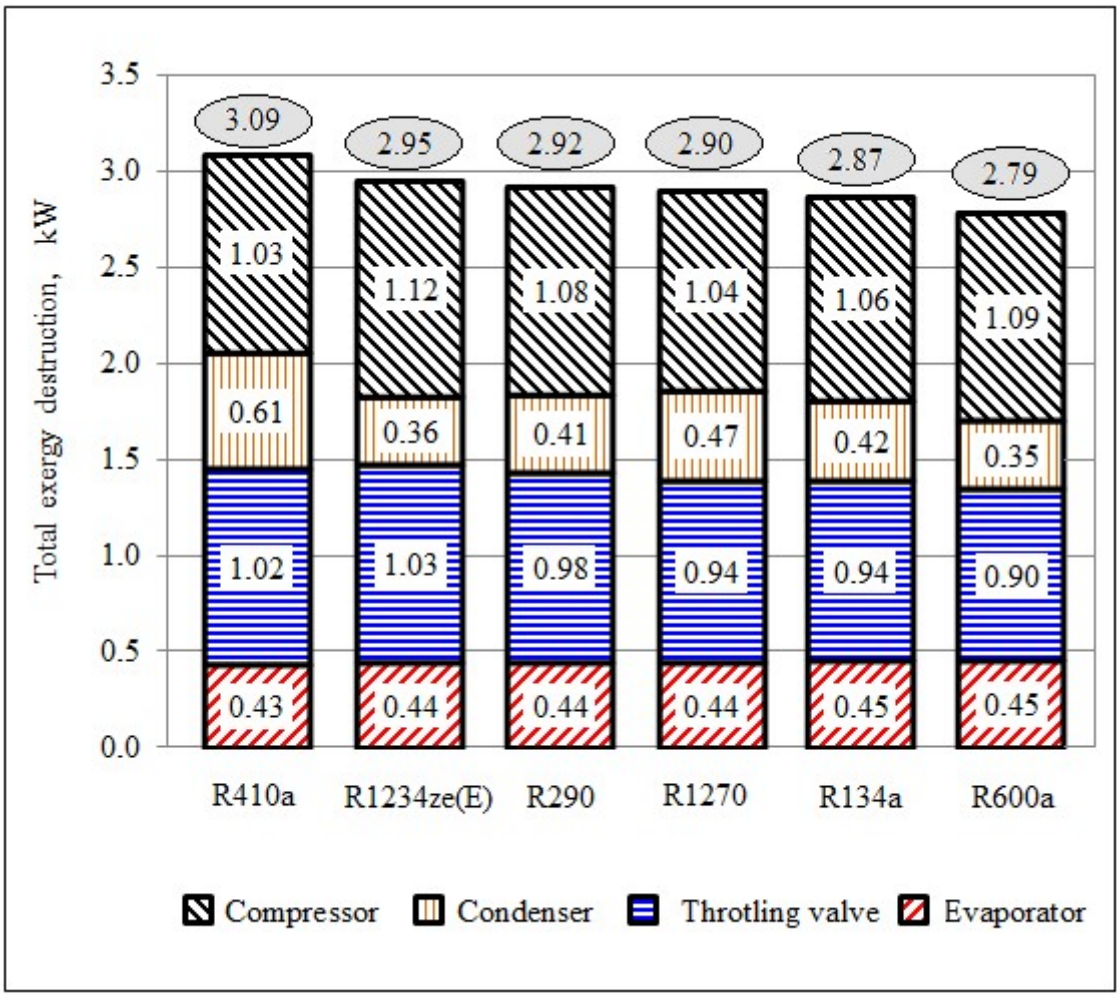

Figure 1: Values of the total exergy destruction $\dot{E}_{D,k}$ (kW) in the components of the investigated heat pump with different working fluids

The values of unavoidable parts of exergy destruction in the compressor, condenser, throttling valve and evaporator for the specified conditions are introduced in Figure. 2. It was possible to notice that, if all the avoidable exergy destruction could be removed, the total exergy destruction would be about halved in all the evaluated cases. In case of applying a R410A cycle the total exergy destruction was decreased by 47%. Compared to R410A R600a, R1270, R290 and R1234ze showed an additional reduction in total exergy destruction of 14.6%, 8.5%, 8.5% and 7.9%, respectively. This decrement was equal to 10.4% for R134a. The biggest decrease of exergy destruction was found for the compressor and this decrease (to the value of about 0.31 kW) was almost the same for all analysed working fluids. For the assumed conditions of unavoidable thermodynamic inefficiencies the highest exergy destruction (between 0.67 and 0.75 kW depending on working fluid) was obtained for the throttling valve.

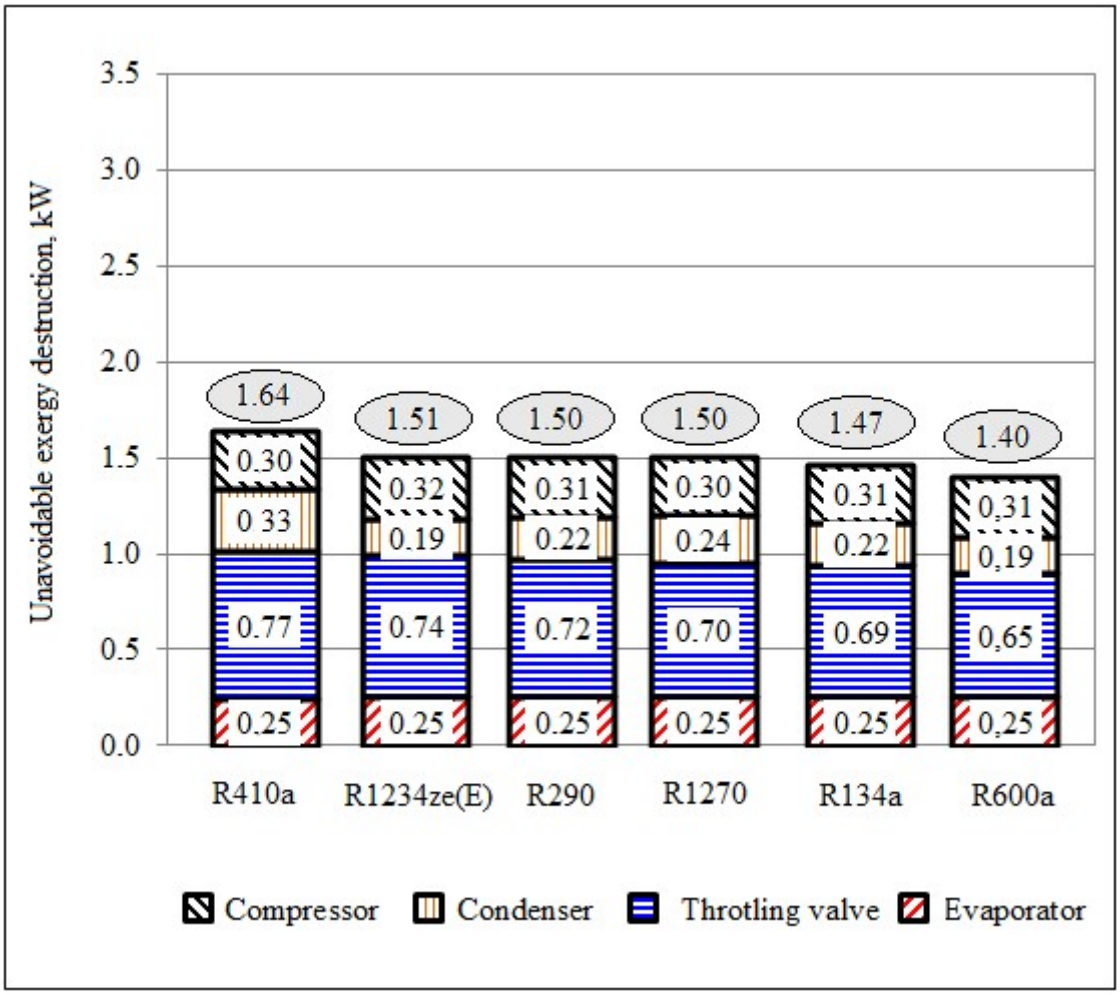

Figure 2: Values of the unavoidable exergy destruction $\dot{E}_{D,k}^{UN}$ (kW) in the components of the investigated heat pump with different working fluids

The values of the avoidable endogenous exergy destruction within the k-th component $\dot{E}_{D,k}^{AV,EN}$ and of the avoidable exogenous exergy destructions within the remaining components caused by the k-th component $\sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,r}^{AV,EX,k}$ for the system with R410A are introduced in Figure 3. It could be observed that 0.3 kW (or 45%) of avoidable exergy destruction in the compressor can be reduced by improving this component. Another part (55%) of avoidable exergy destruction in the compressor was caused by the irreversibilities that occur in the remaining components: evaporator (0.28 kW or 42 %), condenser (0.07 kW or 10 %) and mixed (0.02 kW or 3 %). Also, 0.14 kW (or 34%) of avoidable exergy destruction within the condenser can be reduced by elimination of irreversibilities within the condenser. Another part of avoidable exergy destruction (0.27 kW or 66 %) could be avoided by improving the remaining components: compressor, evaporator and mixed (the biggest share 0.20 kW or 49 %). The results obtained from the advanced exergetic analysis indicated that the endogenous avoidable exergy destruction in the throttling valve is zero. This means that the exergy destruction within this component could be reduced through changes in the remaining components. Evaporator provided 0.21kW (or 50%) of avoidable exergy destruction within the throttling valve. In addition, 0.13 kW (or 31%) of avoidable exergy destruction within the throttling valve were caused by irreversibilities within the condenser. Furthermore, -0.02kW (or 5%) and -0.06 kW (or 14%) of avoidable exergy destruction within the throttling valve depended on irreversibilities taking place in the compressor and combined interactions of more than one components, respectively. According to the results presented in Figure 3 the biggest share of avoidable exergy destruction in the evaporator was endogenous (0.28 kW or 82 %).

It can be seen from the Figure 3 that the biggest value of exergy destruction in the investigated heat pump with R410A could be removed with the help of improving evaporator – the sum of endogenous and exogenous exergy destruction which could be avoided with the help of improving the evaporator was equal to 0.8 kW (or 56%) of all avoidable exergy destruction within the heat pump. Elimination of avoidable irreversibilities within the condenser and the compressor provided 0.29 kW (or 20%) and 0.33 kW (or 24%) respectively of avoidable exergy destruction decrease within the investigated heat pump with R410A.

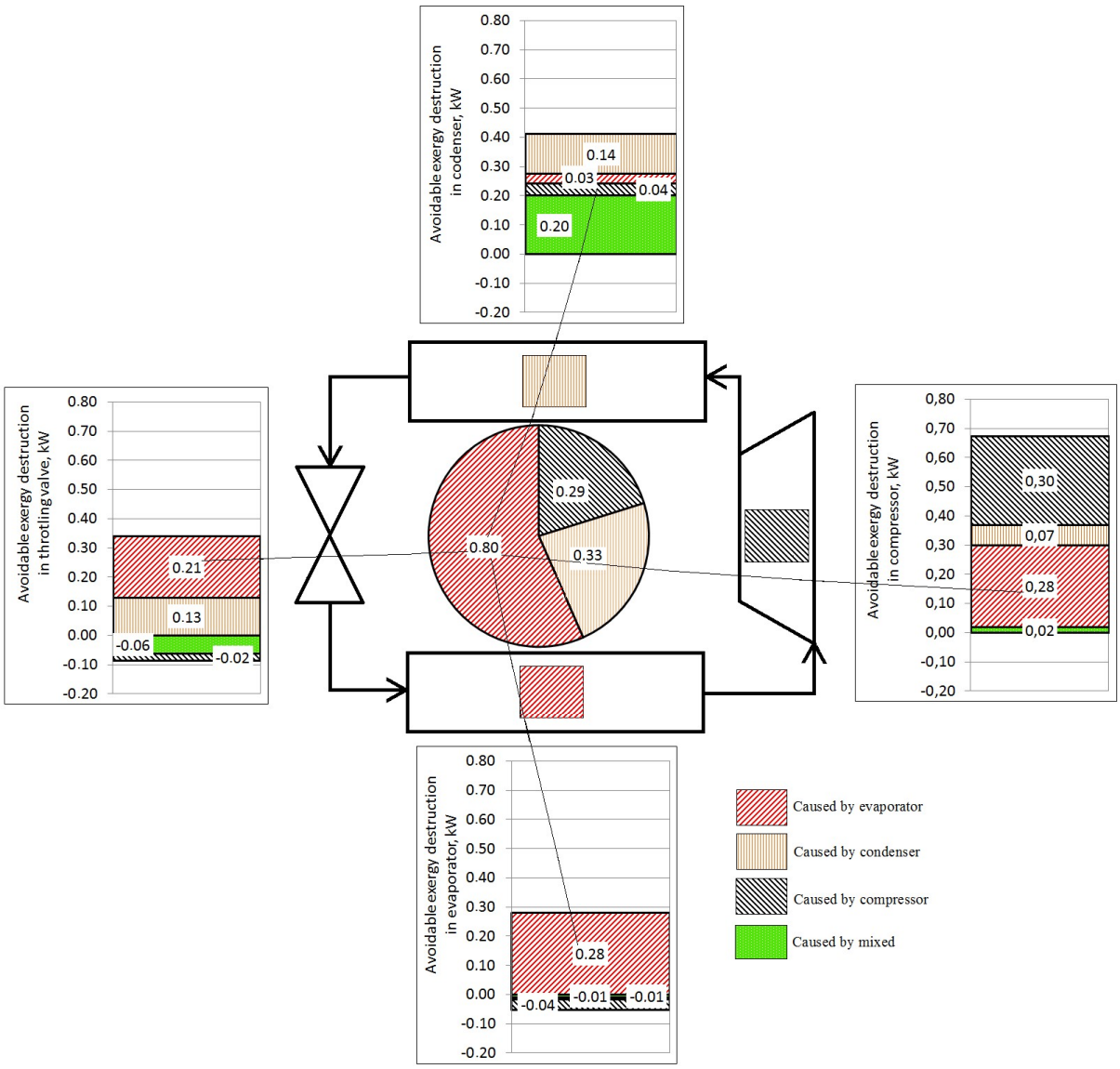

Figure 3: Values of endogenous/exogenous avoidable parts of exergy destructions $\dot{E}_{D,k}^{AV,\Sigma}$ (kW) in the components of the investigated heat pump with R410A

Taking into account the conclusions obtained on the base of advanced exergy analysis (see Figure 3) for the heat pump with R410A and assuming similar results with other working fluids, the next step of calculations were made for the purpose of estimation of exergy destruction in case of removing avoidable irreversibilities within only the evaporator. The results are presented in Figure 4. Generally the priority for choosing working fluid remained the same as in Figures 1 and 2. The same ranking of working fluids in ascending order of the value total exergy destruction was obtained: R600a, R134a, R1270, R290, R1234ze and R410A. It is observed from Figures 1 and 4 that 0.8 kW (or 26%) of exergy destruction could be removed (from 3.09kW to 2.29 kW) in case of using R410A. However, additional decrease of the total exergy destruction could be obtained in case of reducing irreversibilities within

only the evaporator and replacing R410A with R600a (from 2.29kW to 1.99 kW or 13.1%), R1270 (2.11 kW or 7.9%), R290 (to 2.12 kW or 7.5%) and R1234ze(E) (to 2.12 kW 7.5%). This decrement was equal to 2.07 kW (or 9.6%) for R134a.

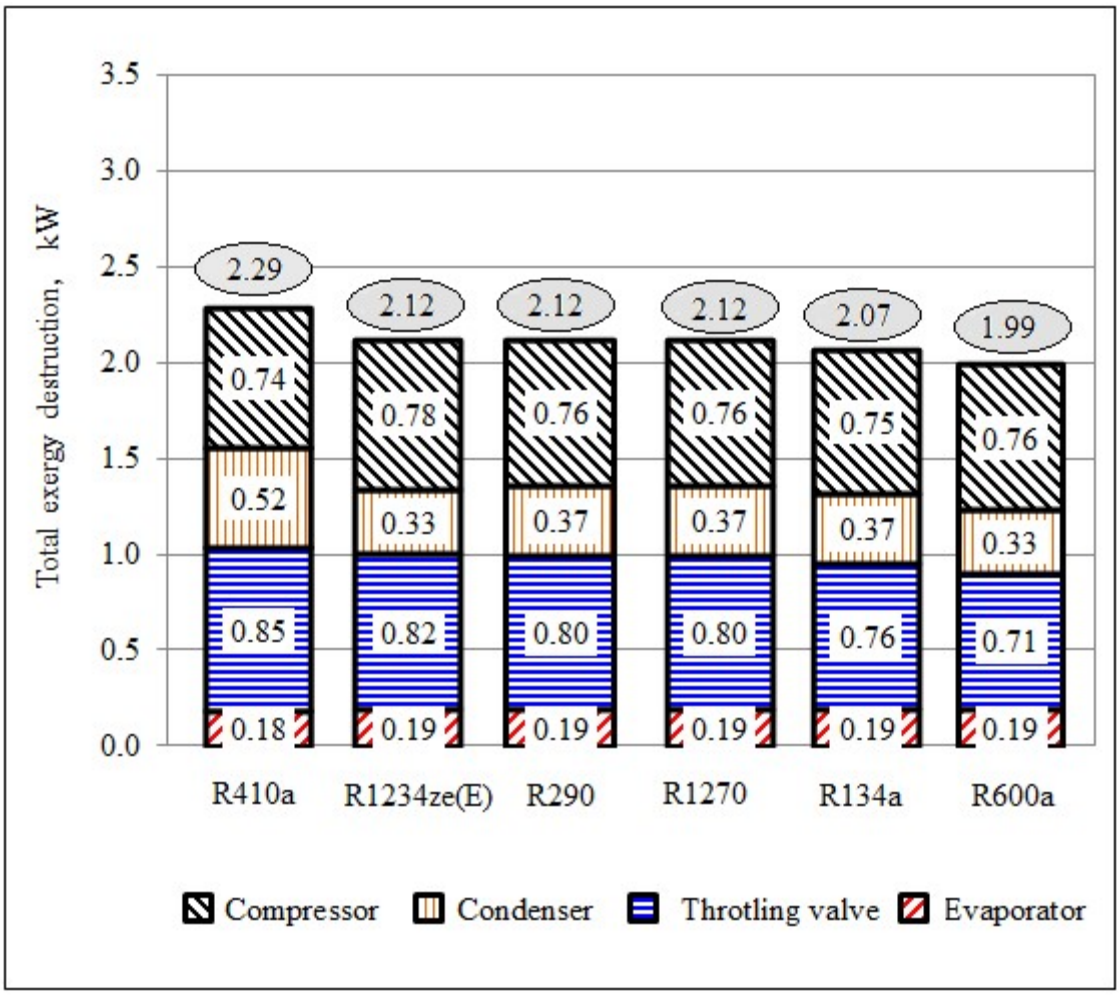

Figure 4: Values of the total exergy destruction $\dot{E}_{D,k}$ (kW) in the components of the investigated heat pump with different working fluids after removing avoidable irreversibilities within the evaporator

4 Conclusions

Advanced exergy-based analysis of the air source heat pump has been made for the purpose to evaluate the most promising alternative among R600a, R290, R600a and R1234ze(E) to R410A and R134a.

The results related to the conventional exergy analysis suggest that the biggest exergy destruction belongs to the thermodynamic cycle with R410A. The lowest value of exergy destruction (2.79 kW) has been obtained for the system with R600a. Therefore, from the thermodynamic viewpoint the priority for selecting working fluids is the following: R600a, R1270, R290 and R1234ze(E).

In case of all the avoidable exergy destruction of R410A heat pump could be removed, the total exergy destruction of this solution would decrease by 47%. Compared to R410A, R600a, R1270, R290, R1234ze(E) provide additional 14.6%, 8.5%, 8.4% and 7.9% reduction of the total exergy destruction, respectively. This decrease is equal to 10.8% for R134a.

For the heat pump with R410A, the biggest value of exergy destruction can be removed with the help of improving evaporator – the sum of endogenous and exogenous exergy destruction which can be avoided with the help of improving the evaporator is equal to 0.8 kW (or 56%) of all avoidable exergy destruction within the thermal system. The enhancement of the condenser and compressor provides 0.29

kW (or 20%) and 0.33 kW (or 24%) of the avoidable exergy destruction decrease within the investigated heat pump with R410A, respectively.

Finally, it has been found that, by removing the avoidable irreversibilities within only evaporator, R600a, R1270, R290 and R1234ze(E) offer further decrease of the total exergy destruction respectively of 13.1%, 7.9%, 7.5% and 7.5% compared to R410A. This decrement is equal to 9.6% for R134a. The ranking of working fluids from the thermodynamic viewpoint remains the same. It can be concluded the hydrocarbons are more suitable replacements for R410A and R134a than R1234ze(E) in air-source heat pumps from an advanced exergy point of view. Further work will involve an in-depth advanced exergy-based analysis of various heat pump solutions using additional environmentally benign refrigerants and based on a heating demand obtained from field measurements.

Nomenclature

$\dot{E}$	exergy rate (kW)
Greek symbols	
η	isentropic efficiency (-)
Subscripts and superscripts	
AV	avoidable
AV, EN	avoidable endogenous
AV, EX	avoidable exogenous
D	destruction
k	k-th component
mexo	mexogenous
r	r-th component
UN	unavoidable
UN, EN	unavoidable endogenous
UN, EX	unavoidable exogenous
Abbreviations	
CM	compressor
COP	coefficient of performance
CD	condenser
EV	evaporator
GWP	global warming potential
TV	throttling valve

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References

[1] Nawaz K., Shen B., Elatar A., Baxter V., Abdelaziz O. R-1234yf and R-1234ze(E) as Low-GWP Refrigerants for Residential Heat Pump Water Heaters. International Journal of Refrigeration 2017; 82: 348–365.

[2] Nawaz K., Shen B., Elatar A., Baxter V., Abdelaziz O. R290 (propane) and R600a (isobutane) as natural refrigerants for residential heat pump water heaters. Applied Thermal Engineering 2017; 127: 870–883.

[3] Morosuk T, Tsatsaronis G, Advanced exergy-based methods used to understand and improve energy-conversion systems. Energy 2019; 169: 238–246.

[4] Morosuk T, Tsatsaronis G, Advanced exergetic evaluation of refrigeration machines using different working fluids. Energy 2009; 34:2248-2258.
[5] Akbulut U, Utlu Z, Olcay Kincay, Exergy, exergoenvironmental and exergoeconomic evaluation of a heat pump-integrated wall heating system. Energy 2016; 107: 502–522.
[6] Wu D., Hu B., Wang R. Z., Fan H., Wang R. The performance comparison of high temperature heat pump among R718 and other refrigerants. Renew Energy 2020;154:715-22.
[7] Siva Reddy V., Panwar N.L., Kaushik S.K. Exergetic analysis of a vapour compression refrigeration system with R134a, R143a, R152a, R404A, R407C, R410A, R502 and R507A. Clean Technologies and Environmental Policy 2012; 14: 47-53.
[8] Menlik T., Demircioğlu A., Özkaya M.G. Energy and exergy analysis of R22 and its alternatives in a vapour compression refrigeration system. Int. J. Exergy 2013; Vol. 12, No. 1: 11-30.
[9] Bobbo S., Fedele L., Curcio M., Bet A., De Carli M., Emmi G., Poletto F., Tarabotti A., Mendrinos D., Mezzasalma G., Bernardi A. Energetic and Exergetic Analysis of Low Global Warming Potential Refrigerants as Substitutes for R410A in Ground Source Heat Pumps. Energies 2019; 12: 3538.
[10] Padmanabhan V. M. V., Palanisamy S.K. Exergy efficiency and irreversibility comparison of R22, R134a, R290 and R407C to replace R22 in an air conditioning system. Journal of Mechanical Science and Technology 2013; 27 (3): 917-926.
[11] de Paula C.H., Duarte W.M., Rocha T.T.M., de Oliveira R.N., Maia A.A.T. Optimal design and environmental, energy and exergy analysis of a vapor compression refrigeration system using R290, R1234yf, and R744 as alternatives to replace R134a. International Journal of Refrigeration 2020; 113:10–20.
[12] Byrne P., Ghoubali R. Exergy analysis of heat pumps for simultaneous heating and cooling, Applied Thermal Engineering. 2019; 149:414-424.
[13] Voloshchuk V., Gullo P., Sereda V. Advanced exergy-based performance enhancement of heat pump space heating system. Energy 2020; 205: 117953.
[14] CoolProp: An open-source thermophysical property library: http://www.coolprop.org/#.
[15] Mathcad: engineering calculation software: https://www.mathcad.com/en/
[16] Torio H, Schmidt D. Low exergy systems for high-performance buildings and communities - detailed exergy assessment guidebook for the built environment. 2011. Annex 49 final report.