COMPARATIVE STUDY OF THE PERFORMANCE OF WATER-WATER HEAT PUMP BETWEEN R407C AND OTHER NEW ECO-FRIENDLY REFRIGERANTS
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STUDIUL COMPARATIV AL PERFORMANȚEI POMPEI DE CĂLDURĂ APĂ-APĂ ÎNTRE R407C ȘI ALȚI AGENȚI FRIGORIFICI ECOLOGICI

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DOI: https://doi.org/10.35633/inmateh-66-40

***Keywords:** heat pump, energy efficiency, exergy efficiency, eco-friendly refrigerants*

ABSTRACT

In the paper we presented a comparative analysis of the effect of the refrigerant used on the operation and performance of a heat pump with water-water and heat regeneration. Various sensitivity studies are presented comparatively for some eco-friendly refrigerants (R290, R600a, R454C, R152a) and R407C. Based on the exergetic analysis, the exergy destruction and loss were estimated for each device, depending on the destination and the operating regime. Graphic and numerical results are presented. In conclusion, a comparative analysis of the defined performance coefficient based on energy and exergetic efficiency is presented. The interest of the study is important due to the applicability of geothermal heat pumps in the field of air conditioning of residential and industrial buildings but also in agriculture for animal farms, for drying some agricultural products in a climate with controlled temperature and relative humidity, in addition the water can be used in summer for irrigation.

ABSTRACT

În lucrare este prezentata o analiză comparativă a efectului agentului frigorific utilizat, asupra funcționării si performanțelor unei pompe de caldură cu regenerarea caldurii de tip apa-apa (geotermală). Diverse studii de sensibilitate sunt prezentate comparativ pentru câțiva agenți frigorifici eco-friendly (R290, R600a, R454C, R152a) și R407C în vederea reducerii emisiilor de seră. Pe baza analizei exergetice s-au estimat pentru fiecare aparat, în funcție de destinație și de regimul de funcționare, distrugerea de exergie si pierderea de exergie. Sunt prezentate rezultate grafice și numerice. În concluzie, se prezintă o analiză comparativă a coeficientului de performanță definit pe baza energetică și a randamentului exergetic. Interesul studiului este important datorita aplicabilității pompelor de caldură geotermale în domeniul climatizării clădirilor rezidențiale și industriale dar și în agricultură pentru fermele de animale, pentru uscarea unor produse agricole în climat cu temperatură și umiditate relativă controlate, dar și pentru irigare.

INTRODUCTION

This paper deals with a comparative analysis of the refrigerant impact on a heat pump with water-to-water heat recovery. The situation of heating and air conditioning for residential, commercial, industrial spaces must be seen in the current context of reducing fossil fuel consumption and using renewable and recoverable energy sources, but also reducing CO2 emissions to limit global warming. This fossil fuel reduction program was set after two weeks of negotiations between world leaders at the 26th United Nations Climate Change Conference (COP26) held in Glasgow in October-November 2021 *(United Nations Climate Change Conference, 2021).*

Heat pumps are generally recognized as an efficient method of saving energy and are widely used for heating and cooling industrial, commercial and residential spaces, for the production of domestic hot water, *in agriculture* in farms for maintaining an adequate indoor thermal environment and air quality. The use of heat pumps offers energy savings, economic benefits but also a positive effect on the environment by reducing CO_2 emissions in the atmosphere. The heat pump is an ecological and renewable energy technology that

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transforms renewable thermal energy from soil, air or water into useful heat for space heating and cooling, domestic hot water production, reversing the natural heat flow from a lower useful temperature to a higher one. This transformation is achieved with the help of an inverted cycle of a refrigerant *(Gaigalis et al., 2016).* Due to the ratification of the Kyoto Protocol, the use of refrigerants with high GWP (GWP - Global Warming Potential) is gradually restricted and they will be phased out in use for heat pump systems. For this reason, the lack of future for hydrofluorocarbon (HFC) refrigerants due to their high global warming potential (GWP) has directed research interest to natural and low GWP refrigerants.

As a result, in 2017 a comparative study was carried out between two heat pump systems for the production of domestic hot water using different natural refrigerants (CO_2 and R290). Comparing these two systems, it was concluded that the subcritical propane systems presented a higher performance coefficient (between 5% and 20%, depending on the increase in water temperature) and that the subcritical propane system is able to heat water from 30º C to 90º C with up to 11% COP improvement compared to CO2 systems (*Pitarch et al., 2017*).

In the same year a study was carried out that presents a detailed analysis of the feasibility of successfully replacing high GWP refrigerants with low GWP refrigerants with acceptable performance. Thus the hydrofluoroolefin (HFO) refrigerants R1234yf and R1234ze(E) have been considered for use in several heating, ventilation, air conditioning and refrigeration applications due to their very low GWP. Both R1234yf and R1234ze(E) have been shown to replace R134a with comparable performance and without substantial changes to the original system *(Nawaz et al., 2017).*

In 2021, researchers showed that the high-temperature heat pump cycle based on R1233zd(E) has excellent performance and broad application prospects, which plays a positive role in the further development of heat pumps (*Jiang et al., 2021*).

To compare the performance of different heat pumps, six refrigerants were selected and simulated in an ideal cycle, including natural refrigerant (R718), HCs (R600, R601), HFO (R1234ze(Z), R1336mzz(Z)) and HFCs (R245fa). The simulation results showed that R718 has the best system performance and Carnot efficiency (COP/COPCarnot) among all these refrigerants. The experimental comparison also showed that R718 has its unique advantages in heat pump applications (*Wu et al., 2020*).

In 2020, researchers also conducted a comprehensive review of geothermal source heat pumps (GSHP) and air source heat pumps (ASHP). They are studied from different aspects, including with refrigerant change, single-stage heat pump and economizer heat pump. These cycles are analyzed using energy, exergy and from an environmental but also an economic point of view (4E analysis). The results show that the coefficient of performance (COP) and exergetic efficiency values for the GSHP cycle are higher than the ASHP cycle, and the best refrigerant for both is R134A. The economic and environmental analysis also reveals that using the GSHP cycle can save electricity to 239 MWh/year, which reduces CO2 emissions to 140 tons/year and saves costs by $27,280/year compared to ASHP. Moreover, by using an economizer in the heat pump cycle, the COP of the GSHP cycle improved by 9%, the exergetic efficiency by about 6.8%, and the COP of the ASHP cycle increased by about 7.5%, and its efficiency exergetic by 7.4%. It is concluded that the economizer has a significant impact on the GSHP cycle (*Maddah et al., 2020*).

In 2017 another study evaluated the performance of R290 (propane) and R600a (isobutane) as a replacement for R134a (an HFC) for heat pump water heating. The results of the analysis suggest that both alternative refrigerants could provide comparable system performance to the base system containing R134a, with a caveat that the alternative, R290, was found to be a better replacement for R134a, while R600a it is expected to provide similar performance if the compressor size is increased to provide a similar heating capacity (*Nawaz et al., 2017*).

Another work evaluates the low GWP refrigerants R600a, R1234ze(Z) and R1233zd(E) as alternatives to traditional low-pressure HFC refrigerants such as R245fa for heat pump (HP) and organic Rankine cycle (ORC) applications. Thermodynamic and heat transfer evaluation results show that R600a, R1234ze(Z) and R1233zd(E) are valuable long-term low-GWP replacements for traditional low-pressure HFC refrigerants in both HP and ORC applications. (*Longo et al., 2020*)

In 2022, a study of high-temperature heat pumps was made through a multiparametric optimization based on low-GWP refrigerants. The mixtures based on R-1233zd(E) and R-1336mzz(Z) were the most promising ones, as they also comply with the environmental restriction (*Moreno et al., 2022*).

R410A refrigerant has a GWP of 1924, so its impact on global warming is significant. For this reason, various lower GWP alternatives to R410A have been proposed in recent years. Two of them are R452B and R454B with GWP values of 675 and 466, respectively. In this context, studies of the performance of introducing

R452B and R454B refrigerants into a heat pump to replace R410A have been developed. This study identified R-452B and R-454B as potential candidates, respectively. In addition, both refrigerants showed similar COP and cooling (or heating) capacities to systems operating with R-410A, as well as lower TEWI (Total Equivalent Warming Impact) values for most of the studies analyzed. Compared to R410A, the lower GWP alternatives show higher discharge temperatures, lower heating and compression powers and similar COPs. (*Sieres et al, 2021; Guilherme et al, 2022*).

Also, in another investigation carried out in 2020, the impact of five HFC refrigerants such as R125, R134A, R404A, R407C and R507A on the efficiency of geothermal heat pump operation was studied. Energetic and exergetic analysis is used to investigate the influence of temperature variations of the geothermal source exhaust fluid on the operation of the heat pump. The coefficient of performance (COP), exergetic efficiency and exergy destruction were determined for different components. The results show that, in the geothermal heat pump cycle, refrigerants R134A and R125 have the highest and lowest COP, respectively. In addition, increasing the temperature of the exhaust fluid from the geothermal source results in an improvement in the COP. For the mentioned refrigerants, the exergy destruction due to the compressor, as the primary energy-consuming equipment, is between 26.7 and 27.3%, compared to the whole system (*Dashtebayaz et al., 2020*).

Another paper (*Tarlea et al., 2020*) compared the operating performance of a heat pump system using R407CA refrigerant to one using R290. The conclusion was that the heat pump that uses the R290 refrigerant achieves an energy saving of 971kWh, which represents, at the annual consumption level of the heat pump that uses the R407C refrigerant, a saving of 22%, and the ecological performance of R290 is absolute.

It should also be emphasized the research direction that studies the importance of applying geothermal heat pumps in the agro-zootechnical sector, where they are rarely applied but necessary and thus their potential must be verified (*Alberti et al., 2018; Blázquez et al., 2022).*

MATERIALS AND METHODS

System description

We considered a water-water type heat pump (geothermal heat pump) that works in the cycle with mechanical vapor compression in one step, with heat regeneration between the superheating and sub-cooling processes, as shown in Fig. 1. The heat pump works with the R407C refrigerant. The condenser thermal load is $\dot{Q}_{W,h} = 13kW$ and the cold source is groundwater with temperature at the evaporator inlet $t_{wc,1}=10^{o}C$ and providing a temperature of the water at the exit from the condenser $t_{wh,2}=35^{o}C$. In this case, the electrical power consumed by the heat pump is P_{el}=2,07 kW and the superheating degree is 10^{o}C.

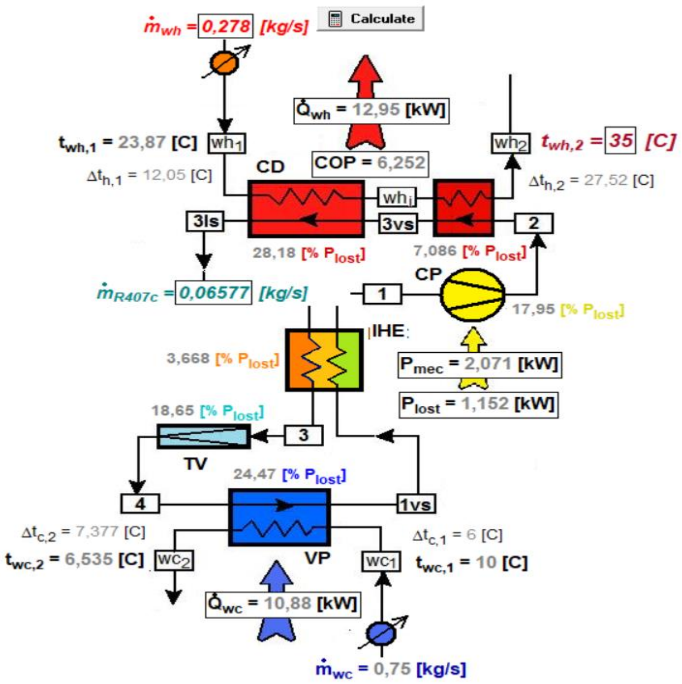
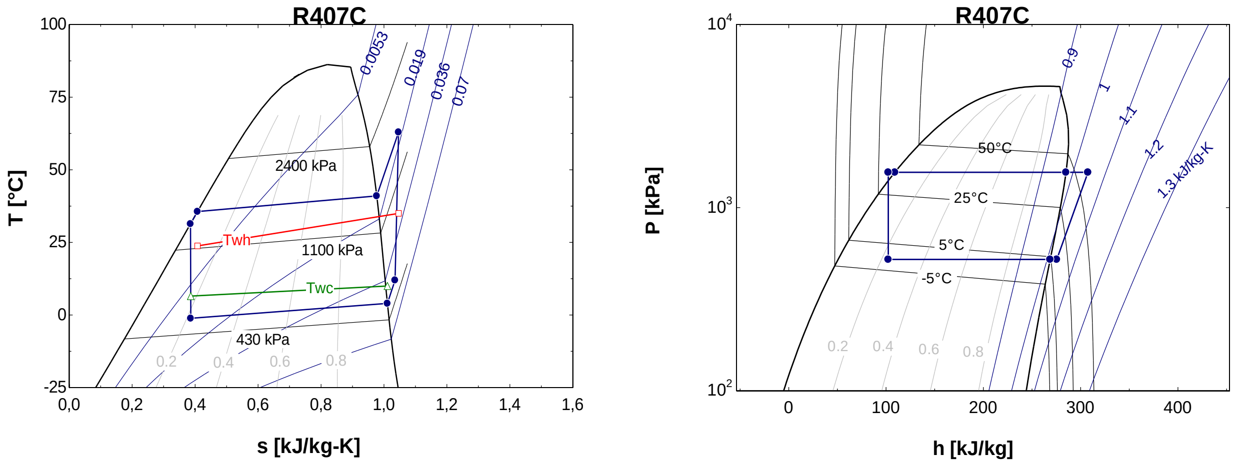


Fig. 1 – Heat Pump with internal heat exchanger
CP-compressor, CD-condenser, VC-vapors cooler, TV-throttle valve,
VP-evaporator, IHE-Internal heat exchanger

The heat pump cycles are represented in T-s and p-h coordinates in Fig.2.



a) **b)**

Fig. 2 – Operating cycle
a) p-h coordinates and b) T-s coordinates

Mathematical model

The system is analyzed both from energetic and exergetic points of view.
Energy analysis is based on the First Law of thermodynamics.

a) Heat transfer rate in condenser:

$$\dot{Q}_C = \dot{m}\cdot(h_{3ls} - h_2) \tag{1}$$

Where: $\dot{m}$ is refrigerant flow rate in [kg/s]; h is specific enthalpy in [kJ/kg].

b) Heat transfer rate in evaporator:

$$\dot{Q}_0 = \dot{m}\cdot(h_{1vs} - h_4) \qquad (2$$

c) The power consumption of compressor can be estimated by:

$$\dot{W}_{Cp} = \dot{m}\cdot\left(h_1 - h_2\right) \tag{3}$$

d) For the throttling valve (throttle process, is enthalpic):

$$\dot{m}\cdot h_3 = \dot{m}\cdot h_4 \tag{4}$$

e) For the Internal heat exchanger (IHE):

$$h_3 - h_{3ls} = h_{1vs} - h_1 \tag{5}$$

f) The energetic efficiency of the system is measured by the coefficient of performance (COP):

$$COP = \frac{usefulleffect}{Consumption} = \frac{\left|\dot{Q}_C\right|}{\left|\dot{W}_{Cp}\right|} \tag{6}$$

g) The volumetric heat capacity (VHC) is used to estimate the heat capacity per volume:

$$VHC = \frac{h_2 - h_{3ls}}{v_1} \tag{7}$$

Where: v_1 is the specific volume at the compressor inlet [m^3/kg].

By applying the Second Law of Thermodynamics to each control volume, one could find the entropy generation in the system. By applying to each device of the system, one gets:

a) For the vapors cooler:

$$\dot{S}_{gen,VC} = \dot{m}\cdot(s_3 - s_2) + \dot{m}_{wh}\cdot(s_{wh2} - s_{whi}) \tag{8}$$

Where: s is the specific enthalpy in [kJ/kg K] and $\dot{m}_{wh}$ is water flow rate at condenser.

b) For the condenser:

$$\dot{S}_{gen,Cd} = \dot{m}\cdot(s_{3ls} - s_{3vs}) + \dot{m}\cdot(s_{whi} - s_{wh1}) \tag{9}$$

c) For the evaporator:

$$\dot{S}_{gen,Vp} = \dot{m}\cdot(s_{1vs} - s_4) + \dot{m}_{wc}\cdot(s_{wc2} - s_{wc1}) \tag{10}$$

d) For the compressor:

$$\dot{S}_{gen,Cp} = \dot{m} \cdot (s_2 - s_1) \tag{11}$$

e) For the throttling valve:

$$\dot{S}_{gen,VL} = \dot{m} \cdot (s_4 - s_3) \tag{12}$$

f) For the Internal heat exchanger:

$$\dot{S}_{gen,\mathrm{Rec}} = \dot{m} \cdot (s_1 - s_{1vs} + s_3 - s_{3ls}) \tag{13}$$

These state parameters (h, s, v) of the refrigerant are determined in each state during the operating cycle by means of the Engineering Equation Solver (EES).

Exergy analysis is based on the Second Law of thermodynamics.

According to Guy-Stodola theorem, the exergy destruction rate is computed by:

$$I = T_0 \cdot \dot{S}_{gen} \tag{12}$$

where I [W] is the exergy destructions rate.

In thermodynamics, the exergy destruction represents a major inefficiency and a quantity to be minimized when the overall system efficiency should be maximized (*Tsatsaronis et al., 2011*)

Total the exergy destructions rate in the whole system can be calculated as:

$$I_{TOT} = I_{VC} + I_{Cd} + I_{TV} + I_{VP} + I_{IHE} \tag{13}$$

The share of the exergy destructions rate of the component k, in the total exergy destructions rate of the system:

$$\Psi_k = \frac{I}{I_{TOT}} \text{ [-]} \tag{14}$$

The exergetic efficiency measures the behavior of the system in relation to the corresponding Carnot cycle. Exergy measures the irreversibility developed in relation to theoretical models.

$$COP_{ex} = \frac{\dot{E}x^{T_c}_{Q_{Cd}}}{\left|\dot{W}_{Cp}\right|} \tag{15}$$

Thermal exergy transfer associated with heat transfer $\dot{Q}_C$ is:

$$\dot{E}x_{Q_c} = \dot{Q}_c \left(1 - \frac{T_0}{T}\right) \tag{16}$$

Whre: T_0 - temperature of the heat source, K; T- temperature of the heat sink, K.

The dead state temperature for the exergetic analysis is considered to be equal to that of the ambient environment which is equal to the temperature of the groundwater t_0=10ºC.

The analysis was performed with the software program Engineering Equation Solver (EES).

RESULTS

Obviously, by its nature, the refrigerant of the cycle in turn influences the performance of the heat pump. The five refrigerants used in the comparative analysis of the heat pump are described in table 2. The thermodynamic agent of the cycle influences the performance of the heat pump and for this purpose we have carried out a sensitivity study. The hot water outlet temperature is the varied parameter for evaluating the performance of the five refrigerants described in Table 2. Following the diagrams 4-14 the different behavior of the five investigated refrigerants can be observed.

Table 2

Some characteristics of refrigerants

Ashrae Number	IUPAC Name	ODP	net GWP 100-yr	Molar mass g/mol	NormalBoiling Point (s) °C	Critical Temp. °C	Critical Pressure (absolute) kPa
R-290	Propane	0	3.3	44.1	-42.1	96.7	4,248
R-600a	Isobutane	0	3.0	58.1	-11.7	134.7	3,640
R-152a	1,1- Difluoroethane (R-152a)	0	124	66,051	-24,7	113,15	44,96
R454C	R32/R1234yf 21.5/78.5	0	146	90.8	--45,9	82.4	38.6
R407C	Tetrafluoroethane	0	1530	86.2	-43.6	86.1	4,62

Regarding irreversibilities, in Fig. 3 one may see the repartition of exergy destruction rates on each component of heat pump system (VC-vapors cooler, Cd-condenser, IHE-internal heat exchanger, Vp-evaporator, TV-throttling valve) for the five refrigerants. The highest exergy destruction rate is in the Condenser for R290, R600a and for R125a. The lower exergy destruction rate is in Vapors Cooler end Internal heat exchanger (IHE) for all the refrigerators.

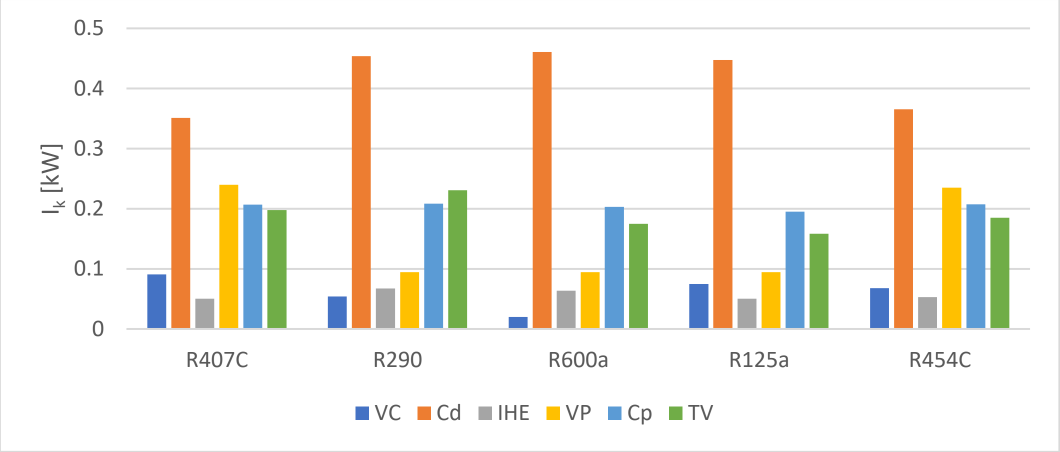


Fig. 3 – Refrigerant effect on the exergy destruction rates for each component of heat pump system

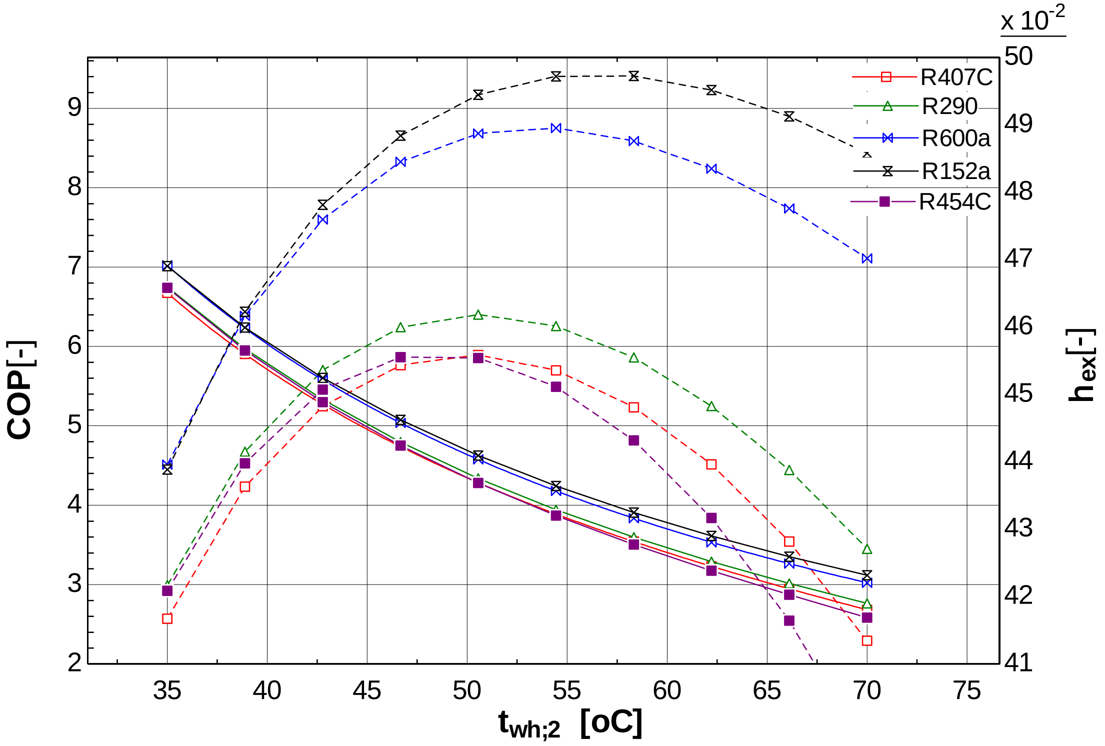


Fig. 4 – Change of COPen and COPex (η_{ex})
for various refrigerants with the hot water outlet temperature

According to Fig. 4, the heat pump cycles using R152a and R600a refrigerants have the highest COP among the compared refrigerants. Due to the increasing temperature of the hot water outlet temperature, the heat output from the panel decreases more than the work of the compressor, thus decreasing the COP. Also, as illustrated, increasing the hot water outlet temperature worsen the COP of the cycle for all the refrigerants. In the same figure, the exergy efficiency calculated by Eq. (5) is shown with hot water outlet temperature from sink source for various refrigerants. R152a and R600a refrigerants have the highest exergy efficiency, and, then, the exergy efficiency decreases for R407C, R290, R507A, and R454C refrigerants, respectively. Increasing the hot water outlet temperature increases the exergy efficiency of the cycle for all the refrigerants between 35 and 55, after that the exergy efficiency decreases for all refrigerants, but has the most significant effect on R152a coolant, after which, R600a, R290, R407A and R545C refrigerants have a greater effect with the hot water temperature of the exhaust from sink source. Refrigerants R407C, R290 and R454C have the lowest exergy efficiency, therefore also the highest exergy destruction. R152a and R600a, the refrigerants having the lowest exergy destruction, also have the best exergy efficiency.

It was presented COPen and COPex in a only figure because the antagonistic situation is interesting: COPen decreases with the increase in temperature tw2 and COPex increases and even shows a maximum. Of course, a compromise between the two situations must be found, which can only be achieved on the basis of a technical-economic study.

In Fig. 5, the work of compressor with the temperature of the hot water outlet from the condenser for R290, R600a and R152a, R407C, and R454C refrigerants is plotted. As shown in Fig. 5, R290, R600a and R152a refrigerants have a higher work. Also, R407C and R454C refrigerants have moderate compressor work. It is also observed that, with the increment of the temperature of the hot water outlet, the compressor work is accordingly augmented.

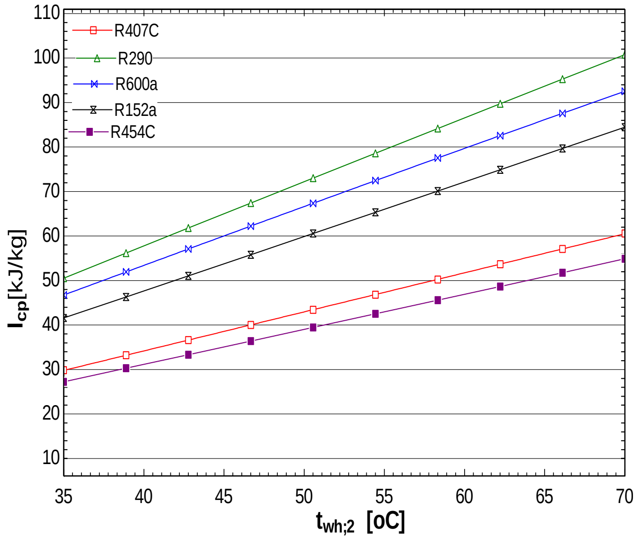


Fig. 5 – **Change of the compressor work for various refrigerants with the hot water outlet temperature**

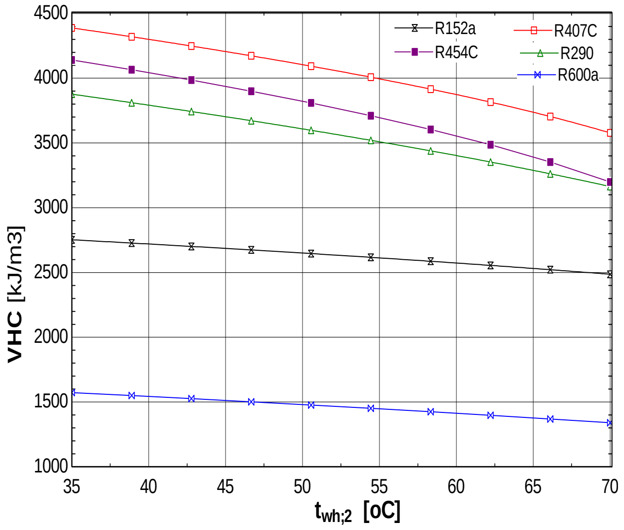


Fig. 6 – **Change of volumetric heat capacity for various refrigerants with the hot water outlet temperature**

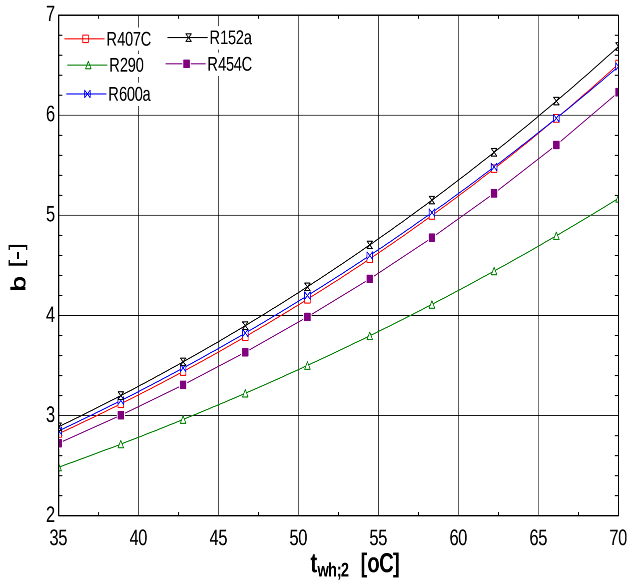


Fig. 7 – **Change of the compressor ratio for various refrigerants with the hot water outlet temperature**

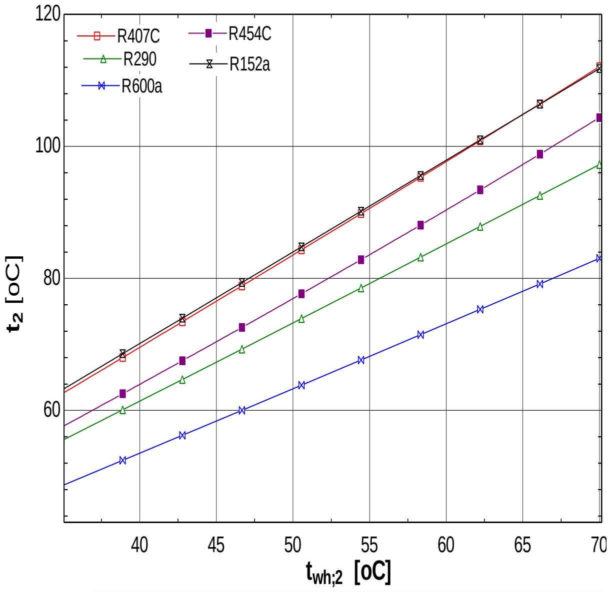


Fig. 8 – **Change of discharge temperature for various refrigerants with the hot water outlet temperature**

Fig. 6 further shows a comparison of the volumetric heat capacity of different refrigerants. According to the calculation results, the volumetric heat capacity of R407C, R454C and R290 is obviously larger than that of other refrigerants and at least twice the volumetric heat capacity of R600a.

The Volumetric Heat capacity is an indicator of the required compressor size. In order to have a small value for VHC (like refrigerant R290) a big size of the compressor is desirable.

When the hot water outlet temperature increases, the condensation temperature and pressure increase. The increased condensation temperature leads to an increase of the pressure ratio, which correspondingly causes the reduction of the volumetric efficiency and the mass flow rate (Fig.7). The final discharge temperature has also been evaluated in Fig. 8.

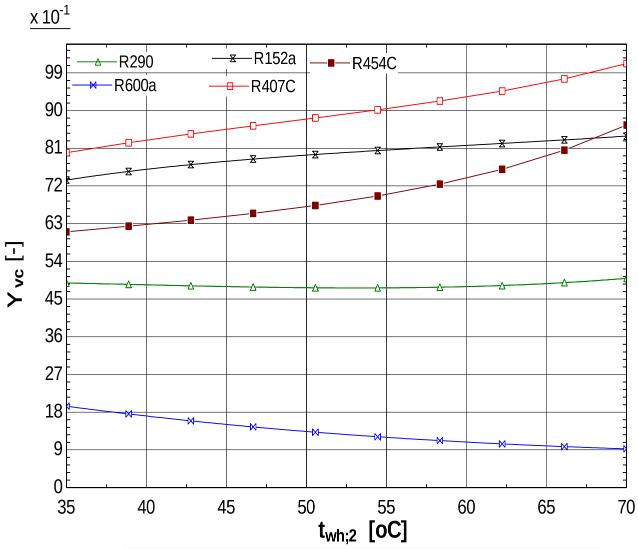


Fig. 9 – **Change of the exergy destruction share in Vapor Cooler for various refrigerants with the hot water outlet temperature**

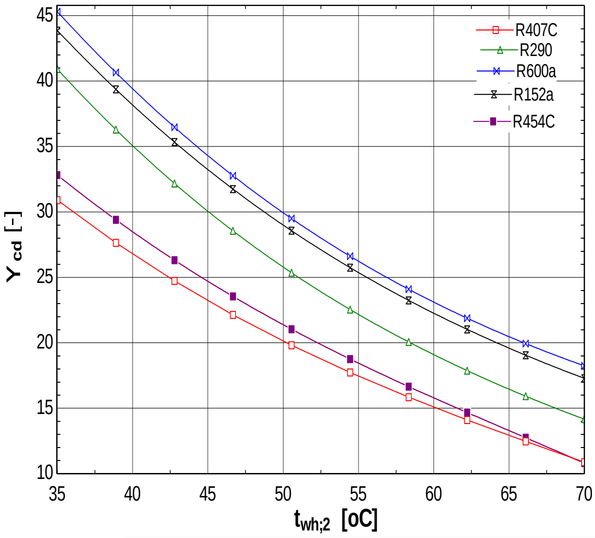


Fig. 10 – **Change of the exergy destruction share in Condenser for various refrigerants with the hot water outlet temperature**

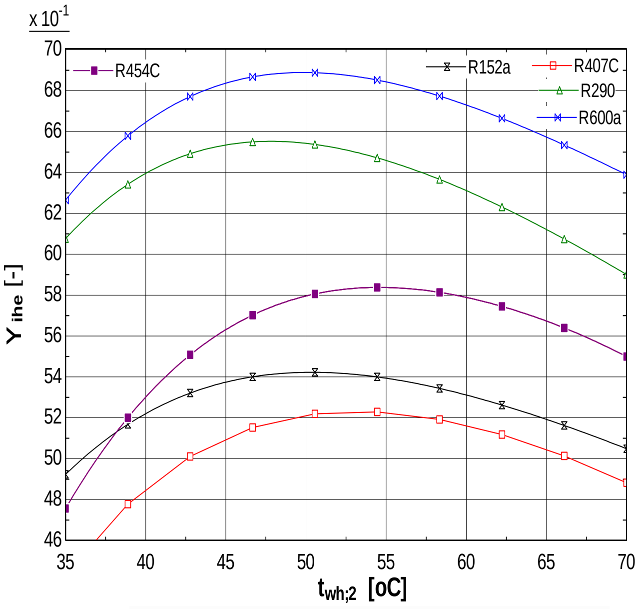


Fig. 11 – **Change of the exergy destruction share in Internal Heat Exchanger for various refrigerants with the hot water outlet temperature**

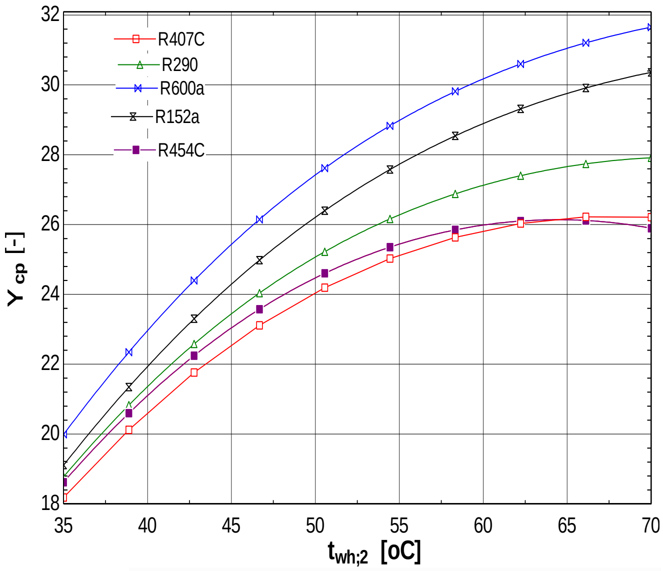


Fig. 12 – **Change of the exergy destruction share in Compressor for various refrigerants with the hot water outlet temperature**

From Fig.10, it can be seen that, at a temperature of 35ºC of the hot water, the share of exergy destruction in the condenser is minimal for the R 407C and R 454C freons. The greatest destruction is observed with R600a and R152a freon. As the hot water temperature increases, the share of exergy destruction in the condenser decreases, which is valid for all refrigerants.

The share of exergy destruction at the internal heat recuperator is shown in Fig. 11 and it is observed that it has the lowest value for R407C freon; followed by the freons R152a and R454C. The other two freons show a greater destruction.

From Fig. 12 it can be seen that the share of exergy destruction at the compressor is the lowest for R407C, R454C, R290. R600a refrigerant has a special characteristic, the trend being the following: when the temperature of the hot water increases, the loss in the compressor also increases.

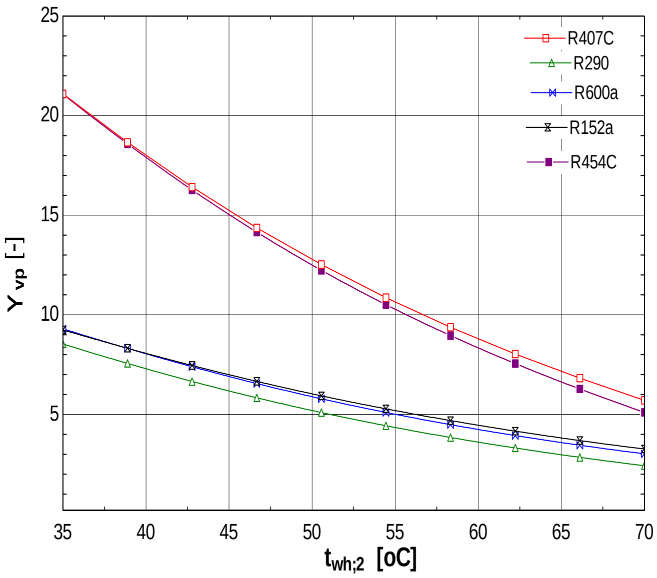


Fig. 13 – Change of the exergy destruction share in Evaporator for various refrigerants with the hot water outlet temperature

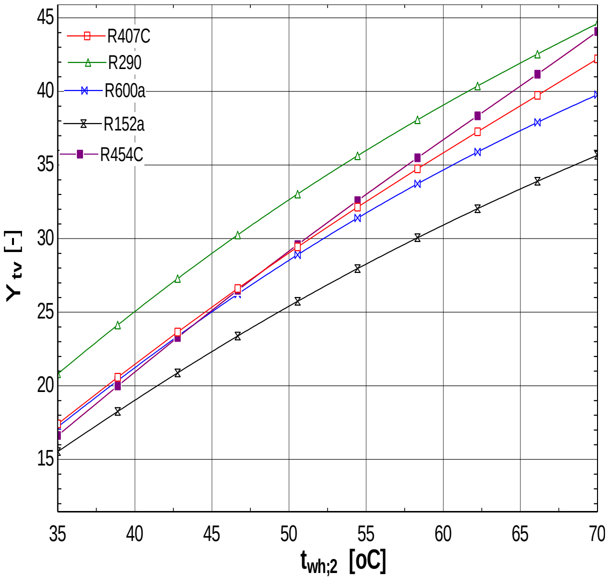


Fig. 14 – Change of the exergy destruction share in Throttle Valve for various refrigerants with the hot water outlet temperature

Following the diagrams in figures 9-14 it is observed that the working agent R600a has a reduced exergy destruction at the level of the vaporizer, but regarding the condensation behaviour, the values of the exergy destruction present due to the heat transfer at the finite temperature difference are high, so following this analysis, it can be seen that the choice of any working agent represents a compromise.

CONCLUSIONS

A comparative analysis of the impact of different refrigerants on the performance of a heat pump was presented. In this paper, current low-GWP refrigerants for conventional heat pumps with a hot water output temperature of 35–70 °C are discussed. The system performance was simulated for different hot water outlet temperatures. Hot water outlet temperature has a remarkable impact on system performance. As the hot water outlet temperature increases from 35°C to 70°C, the COP decreases by 27%, and the heating capacity decreases by 20%.

Based on the exergy analysis, the exergy destructions were estimated for each component of the system in a comparative manner for four ecofriendly refrigerants (R290, R600a, R454C, R152a) proving a different behavior and therefore bringing important information about the optimization of the heat pump system when working with a certain refrigerant. The results obtained in the present research can provide instructions for the design and optimization of efficient geothermal heat pump systems.

The low-GWP refrigerants (R290, R600a, R152a, and R454C) are valid replacements for existing R-407C with comparable, and, in some cases, improved performance metrics. From the ecological point of view, operation with the R290 and R600a refrigerants are the ideal ecological options. Following the COPen and COPex performance indices, it is possible to identify for each of the five investigated agents an optimal point where the equipment performance is maximum.

Finally, further investigations are always needed to find long-term alternative refrigerants that are efficient, environmentally safe and non-flammable.

ACKNOWLEDGEMENT

The authors would like to thank Professor Alexandru Dobrovicescu (University Politehnica of Bucharest) for many helpful discussions regarding exergetic analysis and its applications.

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