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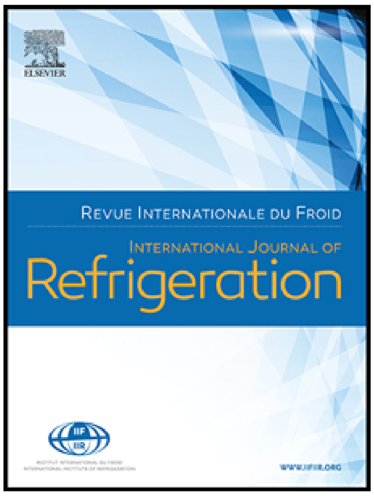

Comparative analysis of HFO-1234ze(E) and R-515B as low GWP alternatives to HFC-134a in moderately high temperature heat pumps

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Highlights

- HFO-1234ze(E) and R-515B are evaluate as low-GWP alternatives to HFC-134a.
- Internal heat exchanger provides significant benefits for heating applications.
- Heating production temperature up to 90 ºC is considered in this study.
- The alternative low-GWP refrigerants provide a significant emission reduction.
- R-515B becomes a promising non-flammable alternative (A1) for heat pumps.

Comparative analysis of HFO-1234ze(E) and R-515B as low GWP alternatives to HFC-134a in moderately high temperature heat pumps

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Abstract

This study provides a theoretical comprehensive performance and environmental analysis of the hydrofluoroolefin HFO-1234ze(E) and the mixture R-515B as alternative low global warming potential (GWP) refrigerants to replace the hydrofluorocarbon HFC-134a in heat pumps. Single-stage cycle, including the use of internal heat exchanger (IHX) has been used as a reference configuration. The influence of an IHX has been simulated to present the benefits of this component in vapour compression systems for medium and moderately high temperature heating applications. HFO-1234ze(E) and R-515B provide around 25% lower heating capacity than HFC-134a due to a diminution of latent heat of vaporization and suction density. The heating capacity difference between HFO-1234ze(E) and R-515B becomes not greater than 2%. The heating coefficient of performance (COP) of the alternative low-GWP refrigerants is comparable to the reference HFC-134a in the conditions proposed. The environmental analysis illustrates that HFO-1234ze(E) and R-515B can reduce down to 18% and 15%, respectively, the equivalent CO_2 emissions compared to HFC-134a in low-temperature space heating applications, and down to 78% compared to a natural gas boiler as conventional heating technology in moderately high temperature applications (domestic hot water, industrial processes, and radiators). Although HFO-1234ze(E) and R-515B present comparable efficiency and environmental performance, R-515B, exhibits an advantage in installation safety requirements as a non-flammable refrigerant (A1).

Keywords: Hydrofluorolefin (HFO); HFC-134a alternative refrigerant; heating capacity; heat pump; energy and environmental analysis

Nomenclature

COP	coefficient of performance (-)
E_a	annual energy consumption (kWh)
$\dot{m}$	refrigerant mass flow rate (kg s^{-1})
n	lifespan of the vapour compression system (years)
L	annual refrigerant leakage rate (kg year^{-1})
P	pressure (MPa)
T	temperature (ºC)
s	specific entropy (kJ kg^{-1} K^{-1})
VHC	volumetric heating capacity (kJ m^{-3})
Greek symbols	
α	recycling factor of the refrigerant

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β	indirect emission factor ($kgCO_{2\text{-eq.}}\ kWh^{-1}$)
ε	effectiveness (-)
Δ	variation
Subscripts	
c	compressor
cond	condensation
crit	critical
disch	discharge
em	electromechanical
in	inlet
k	condenser
o	evaporator
out	outlet
pp	pinch point
r	refrigerant
SC	sub-cooling
SH	superheat
sink	heat sink
suc	suction
source	heat source
Abbreviations	
EES	engineering equation solver
GWP	global warming potential
HCFO	hydrochlorofluoroolefin
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HTHP	High temperature heat pump
IHX	internal heat exchanger
NBP	normal boiling point
ODP	ozone depletion potential
TEWI	total equivalent warming impact

1. Introduction

Vapour compression heat pumps upgrade temperature of an air or water flow by using an electricity input and a wide variety of heat sources. Heat pumps provide primary energy savings compared to natural gas boilers, thanks to the combined effect of their high coefficient of performance (COP) and the low electricity primary energy factor in the analysed context (Jarre et al., 2018). Among different residential power-to-heat options, heat pumps are particularly favourable options because of their beneficial effects on system costs, renewable energy integration, and decarbonisation (Bloess et al., 2018). Specifically, the higher decarbonisation and renewable electricity are, the more competitive heat pumps become in heating grids. Heat pumps can contribute in district heating grids to renewable electricity integration and the expansion of these clean technologies.

Overall, heat pumps are still a growing technology, but a vast deployment is projected, in part driven by tighter regulations on building energy standards and partly also by direct support measures. Already available waste or renewable heat sources could improve the benefits of heat pumps integration. In this way, at European level, applications such as industrial waste heat and geothermal and solar thermal energy are highlighted, among others (Bernath et al., 2019). In this way, heat pumps applications are growing every day, and the variety of sectors is increasing. For instance, it can be used in combination with solar energy combined for covering space heating and domestic hot water demand (Dannemand et al., 2020), or to increase temperature level of waste heat and inject it into district heating networks (Mateu-Royo et al., 2020b), among many other new applications proposed. The application determines the operating temperature level and has an impact on the energy performance of vapour compression heat pumps (Zhang et al., 2020). Therefore, apart from other characteristics such as current and future legislation on environment protection, or high flammability or toxicity (Zühlsdorf et al., 2019), heat sink and heat source temperatures are a critical factor for the selection of the working fluid (Chabot and Mathieu-Potvin, 2020).

R-410A air-to-air heat pumps replacement with lower global warming potential (GWP) refrigerants composed by pure HFC-32 and its mixtures is extensively studied for space heating (Kim et al., 2020) or hot water production with temperatures up to 50°C (Qiu et al., 2019). For higher temperature levels reached in the industry (100-150°C), (very) high temperature heat pumps are a possibility, using HFC-245fa as refrigerant, or some of their low global warming potential alternatives (Arpagaus et al., 2018). (Sun et al., 2019) proposed refrigerant pairs for heat supply temperature of 90°C for air source heat pumps but ended with refrigerants with safety concerns. Then, for hot water supply up to 75 °C, (Xu et al., 2020) proved the carbon emission reduction when substituting fossil fuel boiler by heat pumps but using the high GWP refrigerant HFC-134a. Therefore, there is still a gap for researching the development of heat pumps between 75 and 100 °C using safer fluids with low environmental impact. The selection of the working fluid must be made attending to many requirements, including an adequate critical temperature.

The HFO-1234ze(E) is a hydrofluoroolefin that appeared as low GWP alternative to HFC-134a due to the similar values in the coefficient of performance (COP). However, the use of HFO-1234ze(E) in HFC-134a systems can cause a 20-30% drop in cooling and heating capacity, and it is intended for new design or redesigned vapour compression systems (Mota-Babiloni et al., 2017). Up to now, HFO-1234ze(E) has been widely studied in refrigeration systems (Mota-Babiloni et al., 2016). However, HFO-1234ze(E) critical temperature is 109.4 °C, and there is an untapped potential in the use of this refrigerant in moderately high temperature heat pump systems.

To replace HFC-134a, apart from pure HFOs, several mixtures with low or non-flammability have been developed by Heredia-Aricapa et al., (2020). The development of mixtures depends on many characteristics that can be altered by the selection of component fluids and their composition. Currently, there is no alternative that matches all aspects required to a perfect refrigerant (Dincer, 2018). Bell et al., (2019) proved that a non-flammable alternative for HFC-134a with comparable COP and volumetric capacity ends with a GWP above 500. For example, R-450 and R-513A non-flammable mixtures have been tested up to a condensing temperature of 60°C with promising results but a GWP of approximately 550 (Makhnatch et al., 2019).

Recently, the mixture R-515B (HFO-1234ze(E)/R-227ea (91.1/8.9 in mass percentage) has been developed as a lower GWP replacement for HFC-134a. It presents a GWP of 299, comparable COP and lower heating capacity. One of the benefits of this refrigerant is its classification as a non-flammable refrigerant by the ASHRAE (A1) (Honeywell, 2020). However, due to its recent development, its potential to replace HFCs in applications such as air- and water-cooled chillers, heat pumps or high ambient air conditioning or high stage of cascade systems, among others, has not been yet comprehensively studied.

There is a lack of studies that consider low GWP refrigerants in heat pumps for a temperature production up to 90 °C, and none of them have still considered the new mixture R-515B. The aim of this paper is to investigate the feasibility of HFO-1234ze(E) and R-515B as low GWP refrigerants to replace HFC-134a in heat pump systems and extend the heating production range. First, a selection criterion used to justify the suitability of HFO-1234ze(E) and R-515B, among other low GWP fluids has been applied. Next, the main characteristics of both alternatives are presented and compared to HFC-134a. Then, while the performance of both alternatives is compared with the HFC-134a at temperature up to 75 ºC. In the following, the operation of both low GWP refrigerants is comprehensively studied between 75 and 90 ºC, to extend the operation of heat pumps at moderately high temperature applications, where HFC-134a cannot be used. Finally, an environmental evaluation exhibits the benefits of low GWP alternatives, and the heat pump technology compared to high GWP fluids and fossil fuel burners.

2. System description

2.1. Research scenario and potential heating applications

The schematic of a standard vapour compression cycle with an IHX and its potential heat sources and applications are shown in Fig.1. This system has become the reference configuration in heat pump technology and, therefore, it is selected for this comprehensive analysis of moderately high temperature heat pumps. It is composed by the four main components in vapour compression cycle: compressor, condenser, expansion valve and evaporator and, furthermore, it includes an IHX between the suction and the liquid line that increases the sub-cooling and superheating degree, transferring heat from the condenser outlet to the compressor suction.

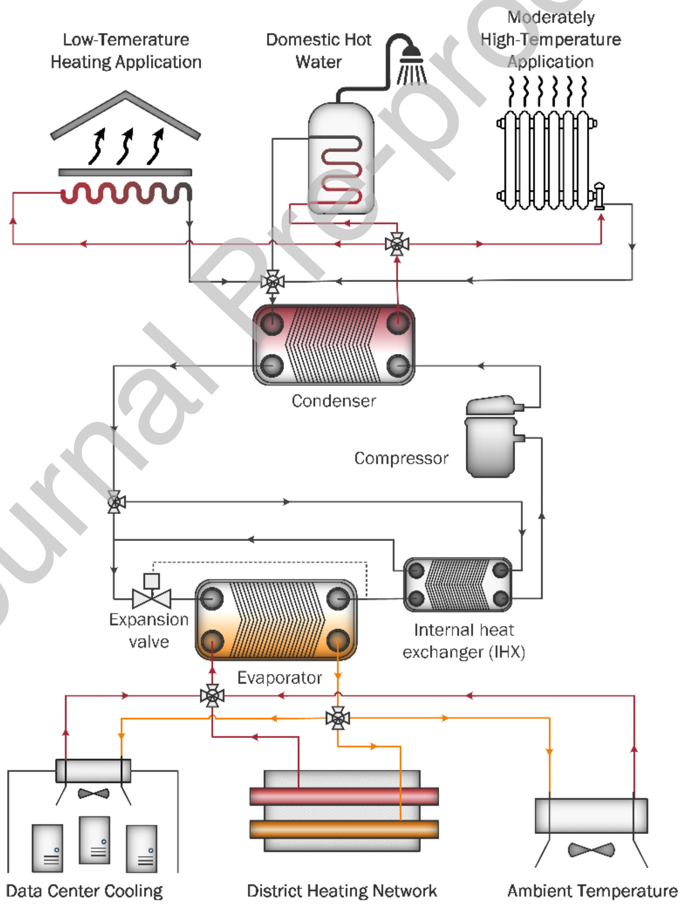


Fig. 1. Schematic of the moderately high temperature heat pump system with potential heat sources and heating applications.

Table 1 illustrates the different temperature ranges of each application, where the integration of moderately high temperature heat pump can be possible, providing significant benefits compared to the traditional heating technology.

Table 1. Traditional heating technology for different applications.

	Application	Temperature Range	Traditional Technology
Heat source	Ambient air	0 – 30 ºC (15 ºC)	Multiple technology
	Data cooling center	20 – 50 ºC (35ºC)	R410a based cooling technology.
	Low-temperature district heating	40 – 70 ºC (55 ºC)	Mix technologies (waste-to-heat, gas boiler, coal, etc.)
Heat sink	Low-temperature space heating	35 – 50 ºC	Solar, electric or gas boiler
	Domestic hot water	45 – 65 ºC	Electric or gas boiler
	Industrial process / Radiators heating	75 – 90 ºC	Centralised gas burned system

2.2. Alternative low-GWP refrigerants screening

A basic computational simulation first explores the potential of low GWP alternatives to HFC-134a to extend the operating conditions of heat pumps to higher production temperatures. Consequently, selected refrigerants require similar or even higher critical temperature than this HFC, presenting comparable thermodynamic properties too. Fig. 2 shows the results of the simulation for the actual available low-GWP alternatives for HFC-134a in heat pump systems.

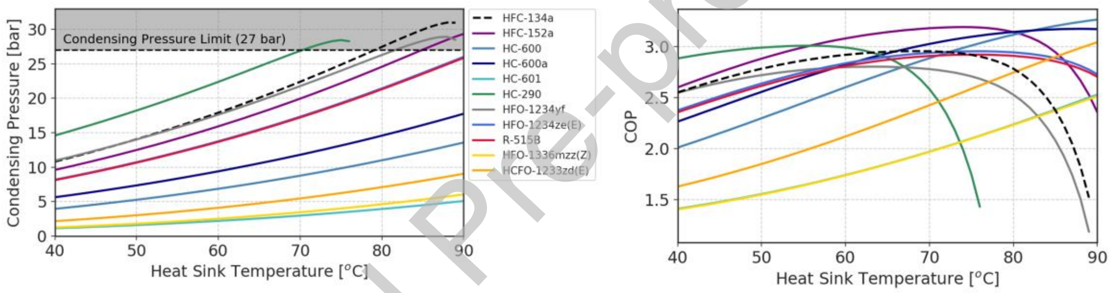


Fig. 2. Condensing temperature and COP screening comparison of low-GWP alternatives to HFC-134a with a lift temperature of 40 K.

Although all the proposed refrigerants could be a candidate to replace HFC-134a in heat pumps, several operating constraints reduce the number of potential candidates. Regarding pressure limitations, maximum condensing pressure of 27 bar is considered due to the components and installation characteristics. Several alternatives exceed the pressure limitation at moderate heat sink temperatures (Fig. 2). As a result, there are not suitable for this moderately high temperature applications, as those included in this work.

On the other hand, low pressure refrigerants as HCFO-1233zd(E), HCFO-1224yd(Z), HFO-1336mzz(Z) and HC-601 can provide the desired heat sink temperature of 90 ºC without exceeding the maximum condensing pressure. However, they end with lower COP than other alternatives for moderately high heat sink temperature, as shown in Fig. 2. Finally, hydrocarbons HC-600 and HC-600a could be a proper candidate to substitute HFC-134a because of the significant COP increase. Nevertheless, these refrigerants present significantly higher flammability (A3) and, therefore, specific security measures are required to use with these refrigerants.

As a result of this screening, HFO-1234ze(E) and its new mixture, R-515B, are selected to comprehensively investigate potential candidates to replace HFC-134a in moderately high temperature heat pumps. Table 2 shows the main characteristics of both refrigerants, together with the baseline HFC-134a, using REFPROP (Lemmon et al., 2018).

Table 2. Main characteristics of the low-GWP alternative refrigerants to HFC-134a.

Parameters	HFC-134a	HFO-1234ze(E)	R-515B
Molecular weight ($g \cdot mol^{-1}$)	102.03	114.04	119.02
Critical temperature (ºC)	101.06	109.36	108.7
Critical pressure (MPa)	4.06	3.64	3.56
Normal boiling point (NBP) (ºC)	-26.1	-18.95	-18.89
Condensing pressure[a] (MPa)	2.12	1.61	1.60
Vapour pressure[c] (MPa)	0.66	0.50	0.50
Latent heat of vaporization[b] ($kJ \cdot kg^{-1}$)	163.02	154.80	148.18
Latent heat of condensation[a] ($kJ \cdot kg^{-1}$)	124.37	123.84	118.17
Suction density[b] ($kg \cdot m^{-3}$)	50.09	40.64	42.08
Liquid/Vapour density[a] ($kg \cdot m^{-3}$)	996.3/115.6	986.2/91.6	1006.3/95.1
Liquid/Vapour specific heat[a] ($kJ \cdot kg^{-1} \cdot K^{-1}$)	1.80/1.61	1.65/1.33	1.62/1.32
Specific heat ratio[b]	1.61	1.55	1.54
ODP (CFC-11=1) (ASHRAE, 2017)	0	0	0
$GWP_{100\text{-}years}$ (ASHRAE, 2017)	1430	<1	299
ASHRAE Std. 34 safety class (ASHRAE, 2017)	A1	A2L	A1

[a] At temperature saturated conditions of 70 ºC
[b] At temperature saturated conditions of 40 ºC
[c] At ambient temperature of 25 ºC

Although HFO-1234ze(E) and R-515B present similar critical temperature than the reference fluid HFC-134a, both candidates have a potential benefit due to the lower critical pressure compared to the reference fluid. This thermophysical property allows to operate with lower condensing pressure and therefore, achieving higher heating production temperatures than HFC-134a without exceeding the installation pressure limitations. Nevertheless, HFO-1234ze(E) and R-515B exhibit a significant reduction regarding suction density compared to HFC-134a that can produce a decrease in the heating capacity and compressor consumption. Moreover, the resulting heating capacity can be contributed by the slight reduction of the latent heat of condensation of each refrigerant as illustrated Fig. 3. On the whole, similar COP than HFC-134a is expected for the alternative low-GWP refrigerants with a significant heating capacity decrease.

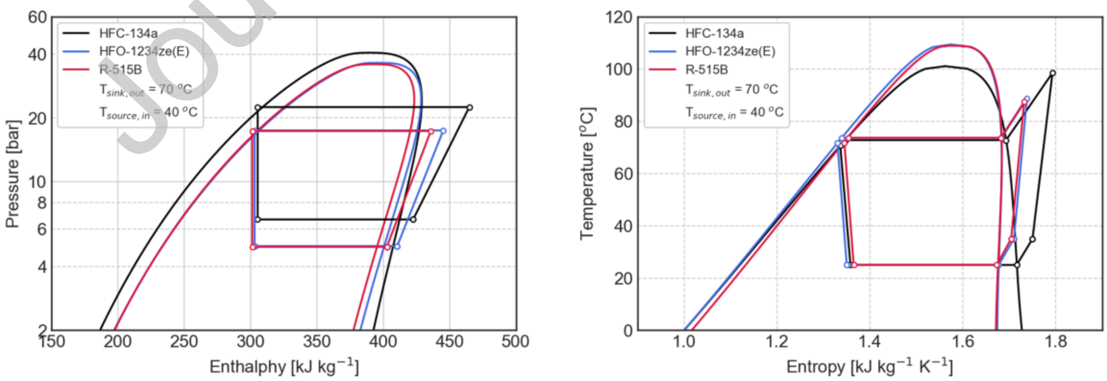


Fig. 3. Thermodynamic P-h and T-s diagrams cycles of HFO-1234ze(E), R-515B and HFC-134a.

The analysis of the properties indicates that HFO-1234ze(E) with a GWP value lower than 1 and R-515 with a GWP reduction up to 79% compared to HFC-134a become a promising low-GWP alternative to reduce the greenhouse gasses emissions. Although HFO-1234ze(E) and R-515B along with the reference fluid HFC-134a have lower toxicity (ASHRAE Class A), there are evident considering flammability characteristics. Whereas HFO-1234ze(E) is classified as A2L due to its lower flammability, HFC-134a and the novel mixture R-515B have no flame propagation, being classified as A1 refrigerant. R-515B contains R-227ea in a small proportion to suppress the mild flammability of the other component, HFO-1234ze(E). R-227ea is as a zero ODP alternative for the fire suppressant Halon 1301 and replaces CFC-114. The significant GWP reduction of the candidates along to the low or even no flammable classification of turn HFO-1234ze(E) and R-515B into sustainable and safe alternatives to HFC-134a.

3. Methodology and modelling details

The strategy, along with the compressor approach, assumptions, and boundary conditions necessary for the modelling, are presented in this section. Special attention is devoted to compressor and heat exchangers modelling given the influence in the cycle performance.

3.1. Modelling strategy

The performance of the heating system is based on the methodology schematised in Fig. 4. Input parameters as refrigerant, boundary conditions, along with assumptions, are introduced in an Engineering Equation Solver (EES) computational model (Klein, 2006). This model includes all the required equations to simulate the thermodynamic cycle and thermophysical properties are retrieved from REFPROP (Lemmon et al., 2018) through an implemented communication between both software. An IHX is included in the simulation to model its influence in the performance response. Nevertheless, design parameters of the IHX require optimisation to maximise system COP without exceeding the discharge temperature limitations. Due to this fact, the Golden Section Search algorithm implemented in EES is used to determine the proper IHX thermal effectiveness. Finally, the optimised results are used as input of the performance analysis based on the thermodynamic model for heat pumps systems described by Mateu-Royo et al., (2020a)

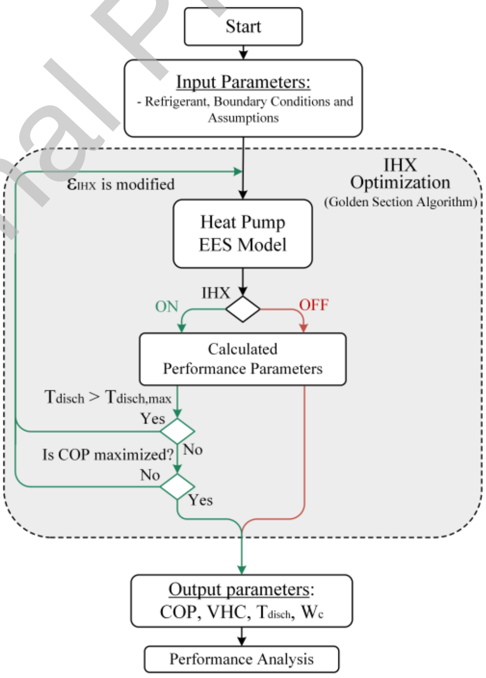


Fig. 4. Methodology flow diagram for the modelling cycle and IHX optimisation.

3.2. Compressor modelling

The compressor can be assumed as the core of a vapour compression system because of its influence on the system efficiency, and it must be adequately modelled. Hence, simulations are based on a commercial scroll compressor for air conditioning applications designed for HFC-134a, with a swept volume of 114.5 cm^3. Moreover, the discharge and suction temperatures have been limited to 150 ºC and 54 ºC, respectively, based on the technical specifications of this component. A vital requisite of the compressor model is able to be providing accurate results when used with different refrigerants. Thus, the scroll compressor model is implemented based on the proposed by Winandy et al. (Winandy et al., 2002), Cuevas et al. (Cuevas et al., 2010) and Lemort (Lemort, 2008). This compressor model has into account the over-under compression phenomena and provides a rigorous approximation to the overall compressor efficiency in a wide range of operating conditions. The electro-mechanical compressor efficiency becomes proportional to the pressure ratio. The proposed compressor model has been validated using manufacturer data. Fig. 5 shows the compressor model and manufacturer results and proves the excellent match between both data.

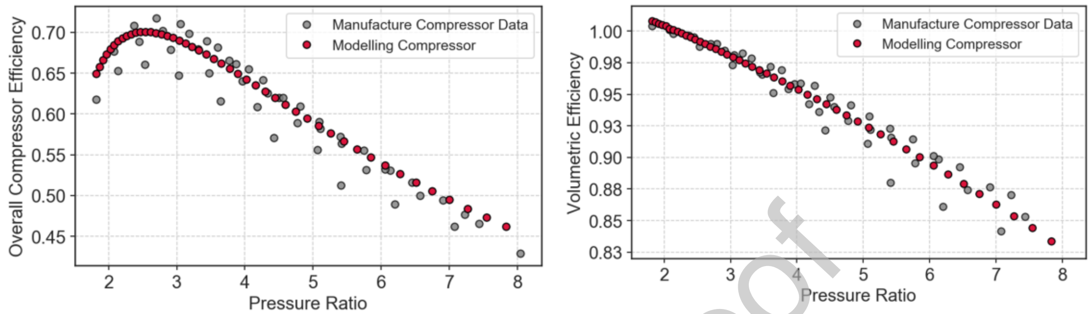


Fig. 5. Overall and volumetric efficiencies results of compressor modelling and manufacture data using HFC-134a as working fluid.

3.3 Assumptions and boundary conditions

Two operating parameters are combined to simulate typical working conditions of the different heat sink and source applications included in Fig. 1: heating production temperature $T_{sink,out}$ and waste heat temperature $T_{source,in}$. Moreover, an isenthalpic process is considered at the expansion valve. The heat transfer to the surroundings and pressure drops are neglected. Table 3 presents the boundary conditions and assumptions.

Table 3. Assumptions and boundary conditions used in modelling simulation.

Parameter	**Assumed value**
Heating production temperature ($T_{sink,out}$)	45-90 ºC
Waste heat temperature ($T_{source,in}$)	15-55 ºC
Superheat degree (ΔT_{SH})	5 K
Sub-cooling degree (ΔT_{SC})	2 K
Condenser approach temperature ($\Delta T_{pp,sink}$)	3 K
Evaporator approach temperature ($\Delta T_{pp,source}$)	5 K
Heat sink temperature glide (ΔT_{sink})	10 K
Heat source temperature glide (ΔT_{source})	10 K

Condenser modelling requires significant attention for heating applications, especially regarding the pinch point between the refrigerant and the heat sink fluid, as shown in Fig. 6. By setting inlet and outlet heat sink temperatures, an increase of the superheat degree caused by the IHX will reduce the condensing pressure and therefore, increase the compressor and cycle performance. Thus, an algorithm has been implemented to find the proper condensing temperature in each operating point, considering the boundary conditions and the superheat degree variation due to the IHX. Finally, evaporator modelling assumptions and temperature approach distribution.

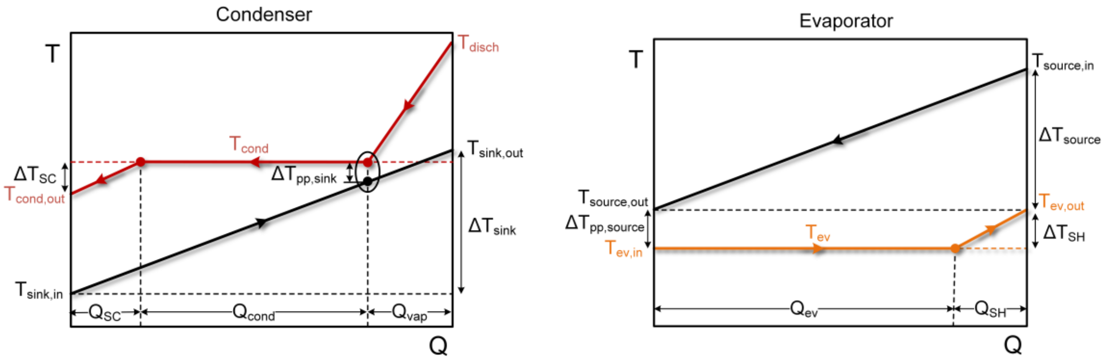


Fig. 6. Condenser and evaporator T-Q diagram with the approach temperatures.

For the IHX, the effectiveness model is used to obtain the heat flow transferred from the condenser exit to the suction line. The effectiveness value becomes limited to not exceed the maximum discharge or suction compressor temperatures, following the manufacture limitations. The most usual type of IXHs used in these applications are based on plate heat exchanger technologies because of the compactness and the heat transfer effectiveness.

4. Results and discussion

This section follows a twofold approach. Firstly, HFO-1234ze(E) and R-515B are compared to HFC-134a until heating production temperature up to 75 ºC, the limit for safe operation (without exceeding the pressure limit) with HFC-134a. Then, HFO-1234ze(E) and R-515B are systemically analysed as potential low GWP refrigerants for moderately high temperature applications up to 90 ºC, for which range is not available today an environmentally friendly, safe, and efficient alternative. Finally, an environmental total equivalent warming impact (TEWI) analysis has been carried out for the twofold approach to calculate the environmental benefits.

4.1. Comparison of low GWP alternatives with HFC-134a

For the given simulations, the resulting mass flow rate is presented in Fig 7. HFO-1234ze(E) and R-515B present around 20% mass flow rate reduction compared to HFC-134a. Moreover, HFO-1234ze(E) shows a slightly lower mass flow rate than its mixture R-515B. This phenomenon is caused by the suction density difference. While suction density results 50 kg m^{-3} for HFC-134a, HFO-1234ze(E) and R-515B present values of 40 kg m^{-3} and 42 kg m^{-3}, respectively. For the same reason, the activation of IHX produces a significant decrease in the mass flow rate in each refrigerant. Thus, a specific IHX influence analysis would illustrate its benefits and disadvantage in the conditions analysed.

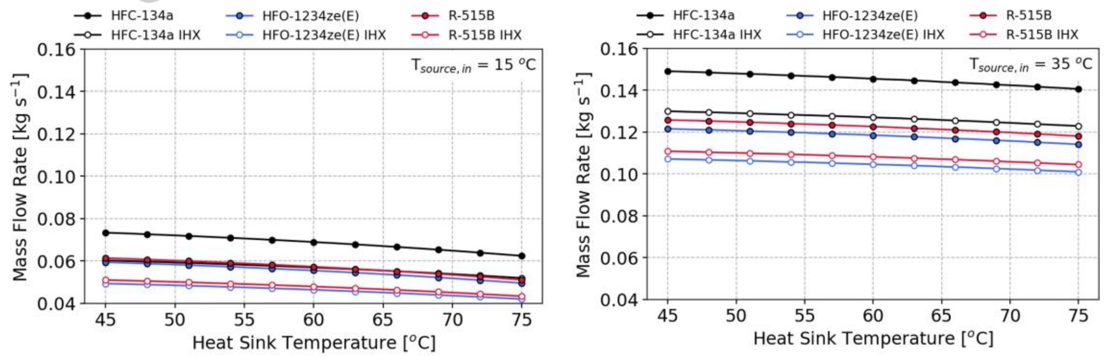


Fig. 7. Mass flow rate analysis of the low GWP alternatives and HFC-134a operating in different heat sink temperatures and two heat sources: 15 ºC and 35 ºC.

Fig. 8 presents the heating effect of each refrigerant, operating with and without an optimised IHX. Like the mass flow analysis, HFC-134a has a higher heating effect than the alternative low GWP refrigerants, but the difference between HFO-1234ze(E) and R-515B can be considered slight. In this case, HFO-1234ze(E) exhibits higher heating effect than R-515B, resulting in benefit for the heating capacity. These minor differences are caused due to the two-phase region variation of each refrigerant, appreciated in Fig. 3.

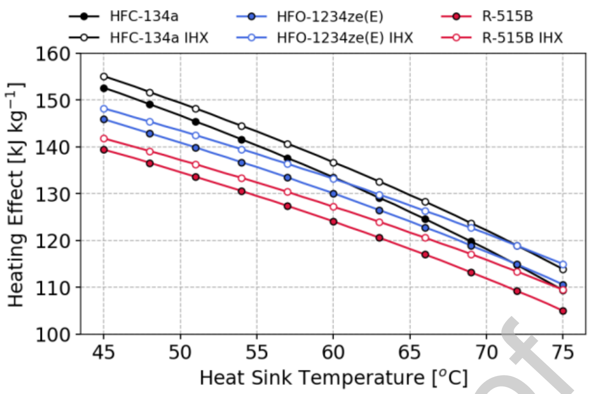


Fig. 8. Heating effect of each considered refrigerant, operating in different heat sink temperatures.

Then, Fig. 9 shows the heating capacity and confirms the expected reduction for the alternatives. HFO-1234ze(E) and R-515B present a significant heating capacity reduction, approximately 25%, compared to HFC-134a, becoming slightly lower this drop when the IHX is activated. This is caused by the mass flow rate and heating effect decrease of the alternative refrigerants previously analysed. As a result, lower heat production or higher investment cost of the compressor size are expected to compensate for the heating capacity drop.

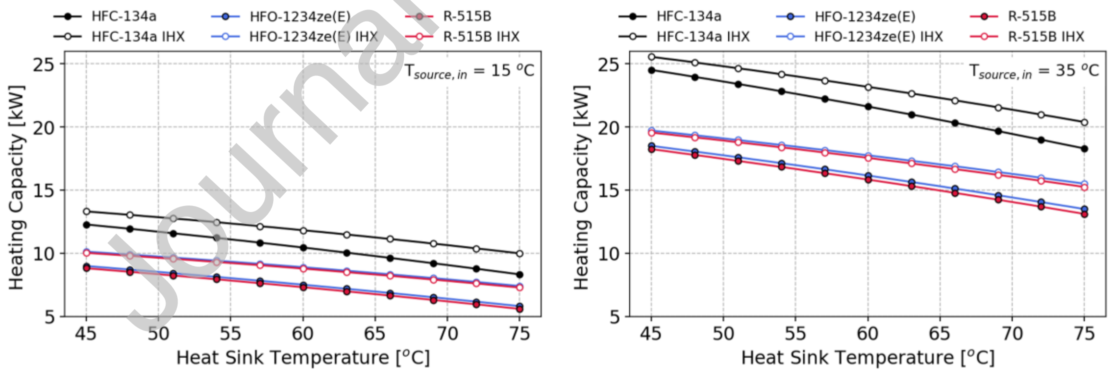


Fig. 9. Heating capacity difference with and without IHX, operating in different heat sink temperature and heat source temperatures: 15 ºC and 35 ºC.

The comparison continues with the study of the energy performance, through the COP, which evolution can be observed in Fig. 10. Without an IHX, the COP of HFC-134a is slightly higher than the alternatives, especially at low heat source temperatures. However, when the IHX is activated, all refrigerants are benefited by an increase in this parameter, it is comparable to the values at low heat source temperature. For high heat source temperatures instead, the alternatives present a benefit at temperature levels up to 60 °C. Under any circumstances, HFO-1234ze(E) provides moderately higher COP than R-515B, lower than 2%.

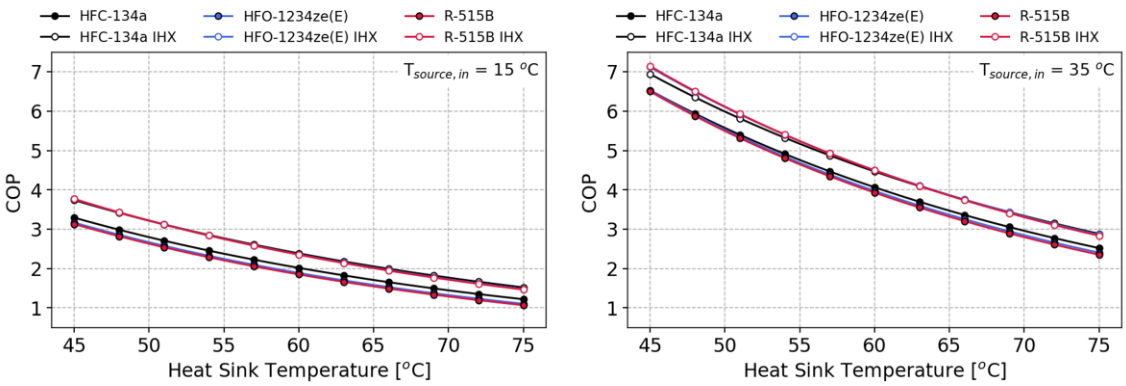


Fig. 10. COP evaluation of HFC-134a and the alternative low-GWP refrigerants for different heat source temperatures: 15 ºC and 35 ºC.

Finally, the discharge temperatures of the alternatives become significantly reduced due to the specific heat ratio differences, previously presented in Table 3. HFC-134a has a considerably higher value of specific heat ratio than the alternatives, whereas, for HFO-1234ze(E) and R-515B, small differences influenced the discharge temperature (Fig. 11). The use of an IHX increases discharge temperature, but always operating below the maximum discharge temperature recommended the compressor manufacturer, 150 ºC.

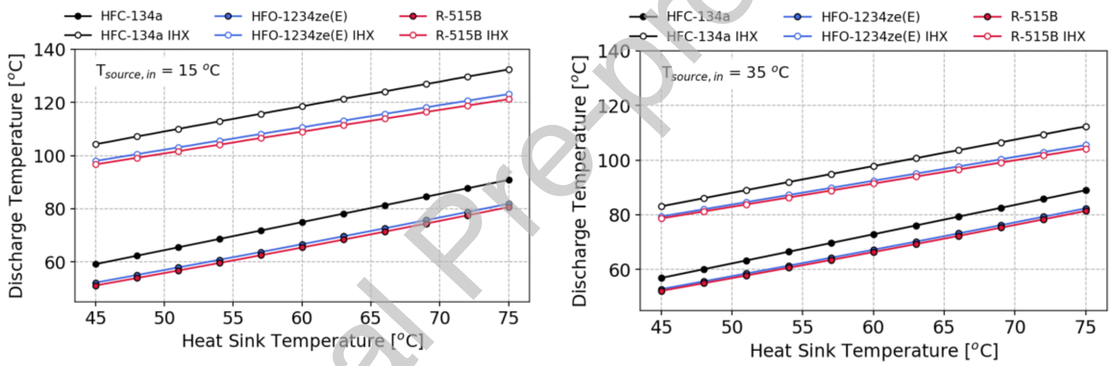


Fig. 11. Discharge temperature evaluation of HFC-134a and the low-GWP alternatives in two different heat source temperatures: 15 ºC and 35 ºC.

Fig. 12 provides a detailed overview of the effect of the IHX on the refrigerants and the different parameters (discharge temperature, mass flow rate, heating capacity and COP). Heat sink and source temperatures of 70 ºC and 40 ºC are selected, respectively, as representing an intermediate operating condition of the simulations. Note that the IHX effectiveness has been set according to the suction and discharge compressor temperatures not to exceed the manufacturer limitations and therefore, ensure the excellent performance of the compressor. The HFC-134a basic cycle without IHX has been used as a reference.

Although it has been expected a heating capacity decrease with the use of the IHX due to the mass flow rate decrease, the heating effect increase can compensate for this phenomenon. Thus, the use of IHX for heating applications slightly improves the heating capacity. Finally, there is a remarkable benefit for the alternatives for the last parameter analysed, the COP. While HFC-134a COP augment is approximately 6%, that of HFO-1234ze(E) is around 17%. Attending these results, it can be concluded that the IHX produces a noticeable effect on the energy performance of the alternative refrigerants, but the heating capacity decrease must be considered in new installations compressor design and selection.

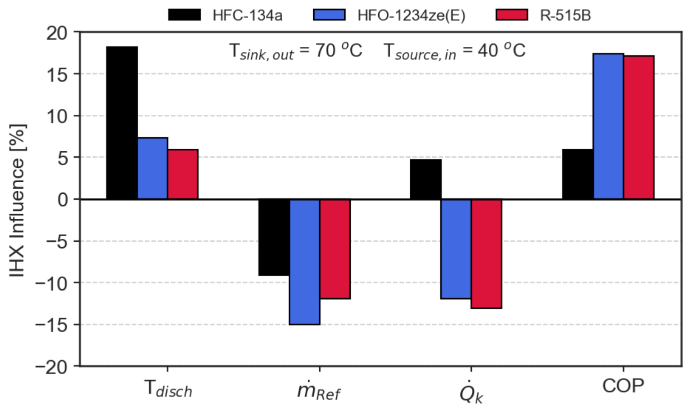
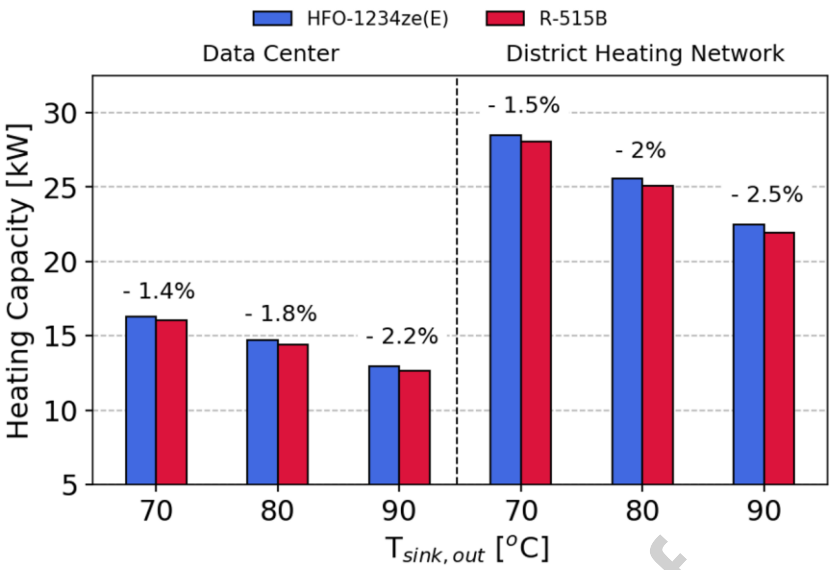


Fig. 12. Comparative analysis of the IHX influence in the performance parameters, using HFC-134a single-stage cycle without IHX as reference.

4.2. Analysis of moderately high temperature production

This section includes the discussion about HFO-1234ze(E) and R-515B as moderately high temperature refrigerants to reach heat sink temperatures where HFC-134a cannot be used due to pressure limitations, as explained in Section 2.2. Heating capacity and COP are selected as the main parameters to be analysed. Data center and district heating network applications are proposed as possible heat sources with an average temperature of 35 ºC and 55 ºC, respectively. Heat sink temperatures of 70, 80, and 90 °C are considered in both scenarios. In contrast to the previous section, Figures show the relative difference between HFO-1234ze(E) and R-515B but taking the pure HFO as the baseline. Fig. 13. demonstrates the almost negligible performance differences between both low GWP refrigerants, with a moderate increase at higher heat source and heat sink temperatures. Therefore, the main HFO-1234ze(E) drawback, its heating capacity, also remains with the new mixture R-515B.

These differences observed in the heating capacity are decreased for the COP. Despite considering validated compressor models that include penalisations for the overall compressor efficiency, the COP values remain at promising levels, varying between 1.8 and 3.3 for data center applications, and between 3 and 5.8 for district heating networks. This energy performance will have a positive impact on CO_2 emissions saving when replacing fossil fuel boilers.



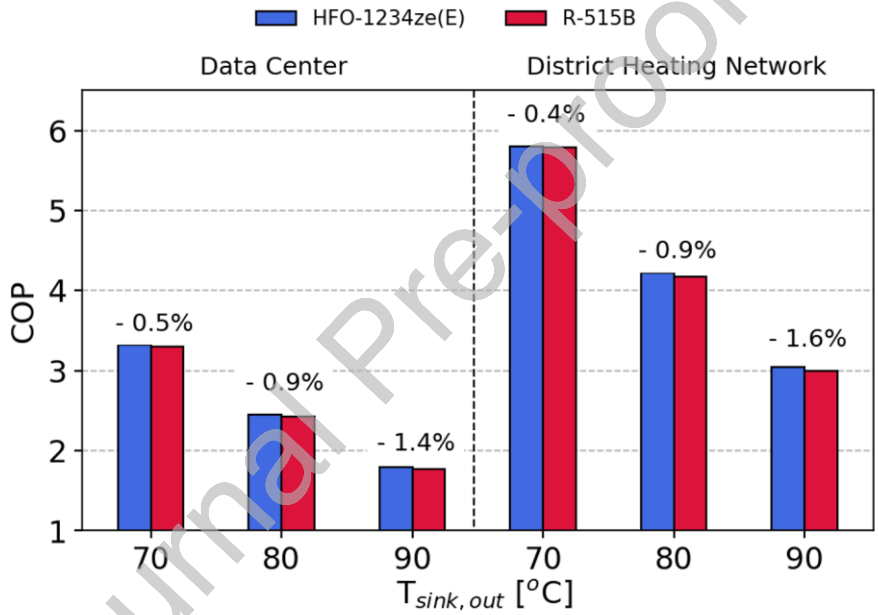


Fig. 13. Heating capacity and COP evaluation of HFO-1234ze(E) and R-515B as low GWP refrigerants for moderately high temperature applications.

This simulation also considers the introduction of IHX with some limitations, and therefore, the energy efficiency is maximised. In contrast, in these scenarios, the IHX effectiveness ranges from 0.1 to 0.4, limited by the compressor suction temperature, which is rather close to the evaporator outlet temperature in the situation of district heating network.

4.3. Environmental study of the proposed scenarios

Finally, an environmental comparison is made between the alternatives and the scenarios proposed. For the case of air source heat pumps (ASHP), Valencia, Paris and Stockholm are considered as proper locations to represent the three European climates (average, colder and warmer) in concordance with the European Directive 2010/30/EU (European Commission, 2013) for the energy labelling of heaters. This European Directive establishes two different thermal levels for the heating production: 35 ºC and 55 ºC for low- and medium-temperature application. Thus, these temperatures are considered in this environmental analysis

TEWI metric has been selected for the environmental evaluation, as it provides representative information of the direct and indirect equivalent CO_2 emissions of vapour compression systems (Makhnatcha and Khodabandeha, 2014). Minimum assumptions must be considered in the TEWI analysis (Eq. (1)). The lifespan of the system (n) is considered 15 years and the recycling factor of the refrigerant (α) is 0.7 (AIRAH, 2012). The refrigerant charge of the system is considered 10 kg, with an annual leakage rate of 5% (IPCC, 2005). Finally, the indirect emission factor (β) considered is the average carbon emission factor for the electricity in the European Union, 295.8 g CO_2 kWh^{-1} (EEA, 2016).

$$TEWI = GWP \cdot L \cdot n + GWP \cdot m_r\,(1-\alpha) + n \cdot E_a \cdot \beta \tag{1}$$

Fig. 14 presents the main results of the TEWI analysis for the case of ASHP in different locations. There is an evident emissions reduction with the use of low GWP alternatives than with the reference fluid HFC-134a. Given the comparable energy performance of three refrigerants considered when using IHX, the indirect emissions result comparable. The significant difference corresponds to the direct emissions of refrigerant, which remains constant for the three cities.

There is 2% difference of CO_2 emission between HFO-1234ze(E) and R-515B mainly caused by the GWP value difference of each refrigerant (1 and 299), respectively. However, R-515B can be an interesting option because is considered a non-flammable refrigerant and would require fewer system and installation safety requirements.

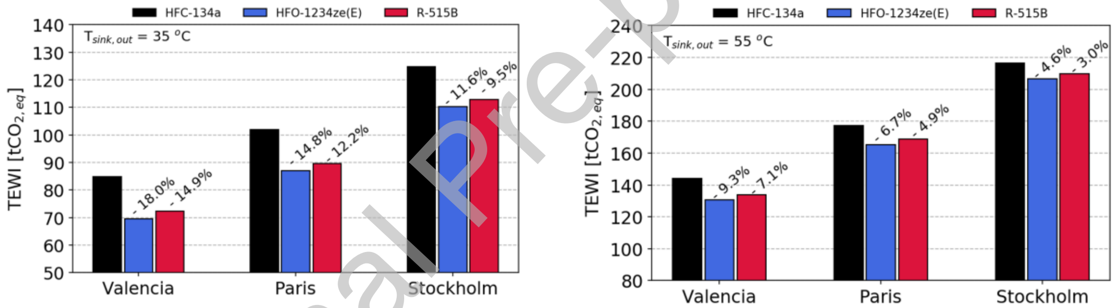


Fig. 14. TEWI analysis of HFC-134a, HFO-1234ze(E) and R-515B as working fluids for ASHP applications.

For moderately high temperature applications, a heat pump system operating with HFO-1234ze(E) and R-515B is compared to a natural gas boiler as its potential environmentally friendly alternative. In this case, the carbon emission factor of natural gas is considered 205 g CO_2 kWh^{-1} (Scoccia et al., 2018). Fig 15 presents the relative difference emission reduction between the heat pump system and a natural gas boiler with the alternative low GWP refrigerants. The substitution of this conventional heating technology with heat pumps can reduce to 77% the equivalent CO_2 emissions. Like the previous analysis, there are minor differences between HFO-1234ze(E) and R-515B caused by the direct refrigerant emission and the GWP value of each refrigerant. However, CO_2 emissions of HFO-1234ze(E) and R-515B remains at a similar level, becoming R-515B more attractive since its considered non-flammable refrigerant (A1).

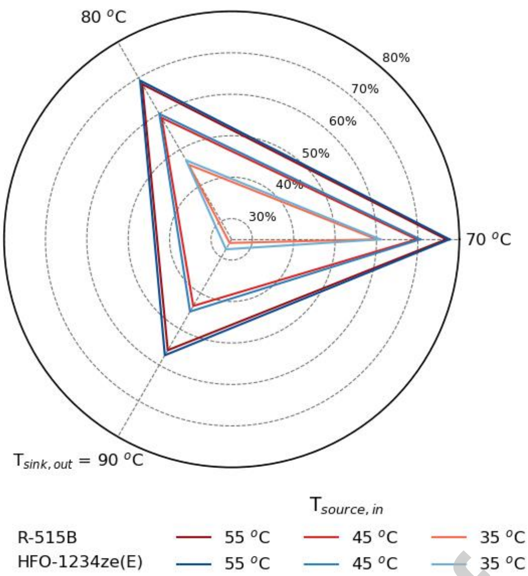


Fig. 15. CO_2 equivalent emissions reduction using a heat pump instead of a natural gas boiler for moderately high temperature applications.

5. Conclusions

This paper provides a comprehensive comparative analysis of HFO-1234ze(E) and R-515B as alternative low GWP refrigerants to replace HFC-134a in heat pump systems for medium and moderately high temperature applications. Additionally, a TEWI evaluation has been included in calculating the equivalent CO_2 emissions of each refrigerant during the operating life. The following conclusions can be drawn from the results of this study:

- HFO-1234ze(E) and R-515B provide around 25% lower heating capacity than HFC-134a due to their thermophysical properties difference. However, the heating capacity difference between HFO-1234ze(E) and R-515B becomes below 2%. The alternative low-GWP refrigerants operate with lower discharge temperature than HFC-134a, which are benefitted using an IHX with higher effectiveness. Both low-GWP alternatives present similar COP that the reference fluid HFC-134a.

- For moderately high temperature applications, HFO-1234ze(E) and R-515B can provide heating production temperatures up to 90 ºC, exhibiting a considerable high performance and therefore, becoming an alternative for conventional heating technology.

- The use of IHXs in heat pumps is strongly recommended to increase the COP of the system along with a slight increase of the heating capacity. Thus, the use of IHX provides flexibility and benefits in heating production.

- The TEWI evaluation illustrates that HFO-1234ze(E) and R-515B can reduce to 18% and 15%, respectively, the equivalent CO_2 emissions compared to HFC-134a in low-temperature heating applications. For moderately high temperature application, the low GWP alternatives can reduce emissions down to 78% compared to a natural gas boiler as conventional heating technology.

- Finally, HFO-1234ze(E) and R-515B present minor difference regarding the performance and environmental analysis. However, R-515B exhibits a significant advantage in the installation safety requirements as a non-flammable refrigerant (A1).

Declaration of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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