Drop-in analysis of an internal heat exchanger in a vapour compression system using R1234ze(E) and R450A as alternatives for R134a

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Abstract

The internal heat exchanger (IHX) is introduced in some refrigeration systems in order to achieve higher energy performances. Results obtained vary greatly depending on the refrigerant used and working conditions. This paper describes a drop-in analysis of IHX effects on the performance of a vapour compression system using R1234ze(E) and R450A (R134a/R1234ze(E) commercial mixture) as R134a low-GWP replacements. The tests were carried out in a completely monitored vapour compression system varying the condensing and evaporating temperature, with and without a counter-current flow tube-in-tube IHX. Because the cooling capacity rises and the power consumption remains similar, the conclusion is that the IHX has a positive influence on the energy efficiency for all refrigerants tested. The COP gain using R1234ze(E) is the highest observed (overcomes the R134a COP for the same conditions). The R1234ze(E) and R450A discharge temperature increments are lower than those of R134a so does not reach dangerous values and the IHX pressure drops are also below than that of R134a.

Keywords: Internal heat exchanger; R1234ze(E); R134a; R450A; energy efficiency; refrigeration.

Nomenclature

A	heat transfer area (m^2)
C	heat capacity rate (kW/K)
$\bar{c}_p$	specific heat capacity at constant pressure (average value) (kJ/kg K)
D	Klein's criteria dimensionless parameter
h	specific enthalpy (kJ/kg)
L	temperature lift (K)

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$\dot{m}_{ref}$	refrigerant mass flow rate (kg/s)
NTU	Number of Transfer Units
P	pressure (kPa)
P_c	power input to the motor (kW)
$\dot{Q}$	thermal power (kW)
T	temperature (K)
U	overall heat transfer coefficient (kW/(m^2 K))
v	specific volume (m^3/kg)
Greek symbols	
ε	internal heat exchanger effectiveness
λ_{T_o}	latent heat of evaporation (kJ/kg)
Subscripts	
$disc$	compressor discharge
in	inlet
k	condenser
L	liquid
min	minimum
o	evaporator
out	outlet
r	relative
V	vapour
Superscripts	
‘	parameters when the IHX is used
Abbreviations	
AHRI	Air-Conditioning, Heating, and Refrigeration Institute

COP	Coefficient of Performance
GHG	Greenhouse gas
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
IHX	Internal Heat Exchanger
ODP	Ozone Depletion Potential
TXV	Thermostatic expansion valve

1. Introduction

Since 1990's, R134a is widely used in medium evaporation temperature refrigeration applications because it presents good energetic performance and as the rest of HydroFluoroCarbons (HFC) fluids, it has zero-Ozone Depletion Potential (ODP). Due to the climate change concern, it was identified as Greenhouse gas (GHG) by the Kyoto Protocol [1]. Through the European Directive 2006/40/EC [2] it was banned in Mobile Air Conditioning systems, being extended this prohibition to other refrigeration and air conditioning applications according to the new F-gas regulation, EU Regulation No 517/2014 [3]. There are diverse low-GWP (Global Warming Potential) options to replace the R134a (GWP of 1300 without climate–carbon feedbacks): natural refrigerants (hydrocarbons and CO_2), low-flammable synthetic fluids (HFO) or mixtures [4].

R1234yf (GWP<1) and R1234ze(E) (GWP<1) are two HFO refrigerants considered promising as low GWP alternatives to R134a [5, 6]. Additionally, they have zero-ODP and although they are classified as A2L refrigerants by ASHRAE [7] (non-toxic and low flammable, high ignition energy with low burning velocity), their flammability highly depend on the humidity of air [8]. Their thermophysical (like density [9] and viscosity [10]) and thermodynamic [11] properties has been recently studied and they are very similar to that exhibited by R134a.

While R1234yf has prevailed as a R134a retrofit and new equipment solution in the field of Mobile Air Conditioning [12, 13], R1234ze(E) (henceforth it will be referred simply as R1234ze) looks promising for new equipment air-cooled and water-cooled chillers [14]. These alternatives present lower cooling capacity than R134a but the same phenomenon happens to the compressor energy consumption, so the Coefficient of Performance (COP) remains similar between them [5].

When mixing refrigerants some shortcomings of the base components are overcame. The HFO/HFC mixtures were identified by the Air-Conditioning, Heating, and

Refrigeration Institute (AHRI) as potential low-GWP replacements for HFC [15], even though no candidate accomplish all the desirable requirements (non-flammable and very low GWP value at the same time) to be used in refrigeration and air conditioning systems [16]. Honeywell International Inc. developed a non-flammable R134a/R1234ze (42/58 mass%) mixture (commercially known as Solstice™ N13 and designed as R450A by ASHRAE, GWP=547) intended to replace R134a [17]. US Environmental Protection Agency (EPA) listed this refrigerant as R134a substitute in refrigeration and air conditioning appliances [18].

Schultz and Kujak studied R450A as R134a replacement in a water-cooled chiller [19]. The cooling capacity and COP reduction were between 12 and 15% and 1 and 4%, respectively. For the rest of AHRI tests, a different composition of definitive R450A was used [20,21]. Honeywell presented very similar cooling capacity and COP in a medium pressure centrifugal chiller application [14]. Mota-Babiloni et al. [22] observed that R450A presents slightly lower cooling capacity and similar COP as R134a drop-in replacement in a vapour compression system at several operating conditions. In a commercial refrigeration system [23], the energetic consumption measured during 48h for R450A was 3.1% lower than that of R134a.

Like system modifications are suggested when using both refrigerants as replacement for R134a, the internal heat exchanger (IHX, also known as liquid-line/suction-line heat exchanger) can be a proper solution to improve the energy efficiency for some refrigerants [24]. The final effect of IHX on the cycle depends on a combination of operating conditions and fluid properties.

In order to predict the IHX results, some authors studied the influence of the operating conditions on the performance when using an IHX, developing theoretical models checking themselves with different refrigerants. Domanski et al. [25] concluded that heat capacity was the most influential property in the benefit of IHX and they developed a model assuming insentropic compression and ideal gas behaviour. Aprea et al. [26] developed a criterion under the hypotheses of adiabatic devices and negligible pressure drops. Klein et al. [27] provide an alternative method of correlating the performance results identifying a new dimensionless parameter and assuming pressure drops in IHX negligible.

Dagilis et al. [28] applied a steady state mathematical model under various operating conditions, giving an optimal inner IHX diameter for household refrigerating systems. Mastrullo et al. [29] developed a simple chart to verify the effectiveness of installation of an IHX using several refrigerants, and they also sustained that the vapour heat capacity is the most influential property on the performance resulting. Hermes [30] highlighted the effect of the evaporating pressure in COP variation for systems with IHX when the cooling capacity is constrained.

Preissner et al. [31] analysed the IHX effects on an R134a automotive air conditioning system, the COP and the capacity resulting with IHX (60 % effectiveness) was increased between 5 and 10 %. In the same way, Desai [32] used a system test bench calorimeter and noticed that IHX can improve the efficiency of an R134a cycle noticeably (11 % with Copper IHX and 7.18% with Aluminum IHX).

Experimental studies performed by Navarro-Esbrí et al. [33] (in a vapour compression system) and Cho et al. [34] (in an automotive refrigeration system) demonstrated how IHX can help to diminish the cooling capacity and COP difference between R1234yf and R134a. Pottker and Hrnjak [35] focused their research on effect of condenser subcooling due to IHX consideration also using R1234yf and R134a.

The aim of this paper is to compare the effect of including an internal heat exchanger in a vapour compression system with R134a and two of its low-GWP replacements, R1234ze(E) and R450A (R1234ze(E)/R134a mixture), as working fluids. The rest of this paper is organized as follows: In Section 2, the experimental test facility is exposed. In Section 3, the test procedure and the equations used in this paper are shown. In Section 4, the experimental results, composed by the influence in compressor efficiencies, cooling capacity, power consumption and cooling capacity, among others, are discussed. Finally, in Section 5, the main conclusions of the study are summarized.

2. Experimental test facility

To carry out the experimental tests with R134a, R1234ze and R450A; a monitored vapour compression system is used as test bench. A schematic representation of the experimental plant is shown in Fig. 1a.

Fig. 1. Schematic diagram of a) the test bench and b) the internal heat exchanger.

The main components of the vapour compression plant are the following:

- A reciprocating open-type compressor, driven by a variable-speed 5 kW electric motor. The lubrication is provided by Polyolester oil.
- A shell-and-tube condenser (1-2), with the refrigerant flowing along the shell and water as cooling fluid flowing inside the tubes.
- A thermostatic expansion valve (TXV).
- A shell-and tube evaporator (1-2), where the refrigerant flows inside the tubes and a water-propylene glycol brine (65/35% by volume) is used as secondary fluid flowing along the shell
- A counter-current flow tube-in-tube IHX (IHX geometric information is provided in Fig. 1.b).

The evaporation and condensation conditions are settled by the load simulation circuit and the heat removal circuit, respectively. The first system uses a set of electrical resistances controlled by a proportional-integral-derivative (PID) system and the second one an auxiliary chiller and a fan coil.

To calculate the refrigerant thermodynamic states pressure gauges and K-type thermocouples are located in the main circuit (their location can be seen in Fig.1a). Refrigerant mass flow rate and compressor consumption are also measured. Two differential pressure transducers are placed to record the IHX pressure drops (vapor side and liquid side). Besides, in the secondary circuits, fluid temperature and volumetric flow rate are measured. Table 1 summarizes the instrumentation characteristics.

Table 1. Measured parameters and equipment uncertainty.

The information is gathered using a data acquisition system. Then it is monitored and stored through a Personal Computer. To obtain the information about the steady state tests, the data is averaged from a time period of 5 min (600 measurements, sample period of 0.5 s) where all the temperatures are within ±0.5 K, the pressures within an interval of ±2.5 kPa and refrigerant mass flow rate is within ±0.0005 kg/s. Finally, the refrigerants thermodynamic states are estimated using the data from tests in REFPROP v.9.1 [36].

The deviation between cooling capacity measured at the refrigerant side and at the propylene glycol brine side is under ±5% limits. In the same way the balance in the internal heat exchanger is also under ±5% limits [37].

3. Experimental procedure and data validation

3.1. Experimental steady-state test

In order to perform a complete assessment of the IHX effect in the refrigeration system, 60 steady-state tests (20 with each refrigerant: R134a, R1234ze and R450A) are carried out varying the following conditions:

- Condensation temperature (T_k): [300-330] K.
- Evaporation temperature (T_o): [260-280] K.
- IHX off/on.

The superheating degree at the evaporator outlet is fixed at 7K by the TXV and the subcooling degree at the condenser outlet was measured 2K at intermediate conditions. The refrigerants purity and the R450A mass fraction are guaranteed by Honeywell International Inc., who provided the refrigerant samples.

In order to compare accurately the IHX effects on the refrigeration system, it is intended to carry out the without/with IHX tests under the most similar conditions. The relative deviations of operating conditions between tests with and without IHX are exposed in Table 2. It can be seen as the absolute average differences are small: 0.2K for evaporation pressure, 0.27K for condensation pressure and 0.26K for superheating degree.

Table 2. Mean operating parameters difference between test with IHX and test without IHX.

3.2 Equations

The IHX effectiveness is calculated applying the counter-current flow case to the vapor compression system, Eq. (1). All the temperatures are measured at the inlet and the outlet of the IHX.

$$\varepsilon_{IHX} = \frac{T_{V,out} - T_{V,in}}{T_{L,out} - T_{V,in}} \tag{1}$$

Can be explained using the efficiency-NTU method, Eq. 2. C_r is the heat capacity ratio and NTU is the Number of Transfer Units.

$$\varepsilon = \frac{1 - e^{-(1-C_r)NTU}}{1 - C_r e^{-(1-C_r)NTU}} \tag{2}$$

NTU is the ratio between the product of overall heat transfer coefficient (U) and heat transfer area (A) between the minimum heat capacity, Eq. (3).

$$NTU = \frac{UA}{C_{min}} \tag{3}$$

The cooling capacity at the refrigerant side is obtained as the product of the refrigerant mass flow rate and the enthalpy increase at the evaporator, Eq. (4).

$$\dot{Q}_o = \dot{m}_{ref}(h_{out} - h_{in})_o \tag{4}$$

Finally, the Coefficient of Performance (COP) is calculated dividing the cooling capacity and the measured power input to the motor, Eq. (5).

$$COP = \frac{\dot{Q}_o}{P_c} \tag{5}$$

3.3 Criteria to determine the IHX influence in COP

Then, the most relevant criteria developed to establish the IHX convenience in a refrigeration system are explained in this section. The variables when IHX is on are represented adding an apostrophe (‘).

Domanski et al. [25] present a method assuming isentropic compression, no-pressure drop at infinite heat exchangers and no pressure drop at IHX, Eq. (6).

$$\text{If } (h_{o,out'} - h_{o,out}) - (h_{o,out} - h_{o,in})\left[\frac{T_{o,out'}}{T_{o,out}} - 1\right] > 0 \rightarrow COP' > COP \tag{6}$$

Aprea et al. [26] develop a criteria under the hypotheses of adiabatic devices, negligible pressure drops in the heat exchangers and the same compression isentropic efficiency in both configurations (with and without IHX), Eq. (7).

$$\text{If } \frac{1}{\frac{\lambda_{T_O}}{\bar{c}_{pV}} - (T_K - T_O)\frac{\bar{c}_{pL}}{\bar{c}_{pV}}} - \frac{v_{o,out'} - v_{o,out}}{v_{o,out}(T_{o,out'} - T_{o,out})} > 0 \rightarrow COP' > COP \tag{7}$$

The criteria developed by Klein et al. [27] supposes that the IHX adoption has no influence on the compressor power consumption. This correlation also obtains an approximation to the COP relative increase due to the IHX activation, Eq. (7).

$$\left(\frac{COP'}{COP}-1\right)100 = \varepsilon(-3.0468 + 19.3484\,D - 19.091\,D^2 + 1.2094\,L + 0.02101\,L^2 - 5.9980\,D\,L - 0.02797\,DL^2 + 5.52865\,D^2L) \quad (8)$$

D is a dimensionless parameter expressed and L is the temperature lift, Eq. (9) and (10).

$$D = \frac{\lambda_{T_o}}{c_{p,L}T_k} \quad (9)$$

$$L = (T_k - T_o) \quad (10)$$

4. Results and discussion

This section presents and discusses the experimental results obtained using R134a, R1234ze and R450A as working fluids. The parameters analysed are the following:

- IHX effectiveness.
- Mass flow ratio
- Cooling capacity.
- Power input to the motor.
- Coefficient of Performance (COP).
- Pressure drop at vapour side
- Compressor discharge temperature.

The main energetic parameters uncertainty (cooling capacity and COP) is calculated using the Root Sum Square (RSS) method [38], Table 3. The rest of parameters uncertainty can be retrieved from Table 1.

Table 3. Main energetic parameters uncertainty.

4.1 IHX effectiveness

As expected, the IHX effectiveness rises with the compression ratio (Fig. 2). This happens because the NTU is greater at high compression ratios and the flow stream capacity ratio decreases. The R1234ze IHX effectiveness is higher than those of R134a. R450A IHX effectiveness presents intermediate values between R1234ze and R134a except at high evaporation temperatures, when its behaviour is more similar to R1234ze. These results can be used to simulate a theoretical IHX cycle considering these refrigerants at various conditions.

Fig. 2. Internal heat exchanger effectiveness.

4.2 Mass flow rate

Prior to analyse the cooling capacity variation, the mass flow rate relative variation is shown in Fig 3. The IHX reduces the mass flow rate of vapour compression system due to a suction specific volume increase that is greater than that of volumetric efficiency, both due to additional superheating. The difference between both effects is higher at low compression ratios and that influences on the mass flow rate reduction.

Fig. 3. Mass flow rate relative variations due to the IHX adoption.

4.3 Cooling capacity

The IHX effect on cooling capacity can be observed in Fig. 4. The major cooling capacity increase is produced at high compression ratios and the most relevant cooling capacity increase corresponds to R1234ze. Although R450A cooling capacity increases considerably, it cannot reach those performed by R134a (without IHX).

Fig. 4. Cooling capacity relative variations due to the IHX adoption.

The cooling capacity augmentation is a consequence of a major specific refrigerating effect increase (due to additional condenser subcooling) than a mass flow rate diminution.

4.4 Power input to the motor

The next relevant energetic parameter analysed is power input to the motor, Fig 5. The power consumption when IHX is activated is similar or slightly decremented compared to basic cycle. The power consumption decrease is due to compressor global efficiency augmentation is higher than the isentropic compressor work increase. Both are affected by the additional superheating at the IHX outlet [39]. The lowest values on the power consumption influence are obtained using R1234ze at low evaporation temperature.

Fig. 5. Power input to the motor relative variations due to the IHX adoption.

4.5 Coefficient of Performance (COP)

COP relative variation quantifies IHX influence on the energy efficiency of the refrigeration system, Fig 6. The IHX produces an increment on COP for all refrigerants, being greater for the alternatives at high compression ratios. As discussed before, while power consumption is slightly reduced by IHX usage, cooling capacity is increased and COP follows its trend. The IHX effect on R450A COP is intermediate and nearer to R134a results. The COP results are always positive even though for low condensation temperatures (300K) these values are much reduced.

Fig. 6. COP relative variations due to the IHX adoption.

The IHX could be included to increase the final energy performance of alternatives when they replace R134a in a system without IHX. Thus the COP results could be slightly lower or slightly higher when a retrofit with IHX is considered using R1234ze(E) or R450A, respectively. The highest positive differences are performed at high compression ratios, due to the cooling capacity increase.

As introduced in section 3.3, some authors have developed different criteria to predict positive or negative IHX influence on the COP of refrigeration systems. Table 4 shows a summary of the criteria's results and Fig. 7 represents the deviation between experimental results and Klein's criterion results.

Table 4. Comparison between Aprea's, Domanski's and Klein's criteria and the experimental results.

Fig. 7. Experimental COP relative variations versus Klein's predictions.

On the one hand, though a qualitative criteria, Aprea's and Domanski's criteria predict correctly the positive effect of IHX in COP for the cases studied. On the other hand, although Klein's criteria (quantitative) generally underpredicts the COP increment in the majority of conditions considered, the deviation between this criteria and experimental results remains under COP uncertainty. Thus, it can be assumed that it provides a good prediction of COP.

4.6 Pressure drop at IHX vapour side

According to Darcy-Weisbach equation, the pressure drop ($\Delta P_{IHX,v}$) is proportional to geometrical parameters of the IHX (equal for all refrigerants tested) and viscosity and velocity of the fluid. R1234ze has lower viscosity and velocity than the R134a, consequently its pressure drops are smaller and R450A presents intermediate values, closer to R134a, Fig. 8. Although the viscosity augmentation influences on pressure drops (through Reynolds Number and then friction factor), mass flow rate (and consequently gas velocity) diminishes with the decrease in compression ratio reduction and this parameter rises the vapour pressure drops.

Fig. 8. Pressure drops at the vapour side of the IHX.

4.7 Discharge temperature

The discharge temperature (Fig. 9) is incremented when the IHX is activated, due to the additional superheating produced at the vapour side and the increasing slope of the isentropic curves. The discharge temperature augmentation rises with the compression ratio due to the behaviour of the isentropic curves.

The increase is higher for R134a than the alternatives, being the discharge temperature increase of R450 between R134a and R1234ze results. Furthermore, the total discharge temperature of alternatives is lower than that of R134a so the final discharge temperature of R1234ze and R450A is still lower than those of R134a and they do not reach (in the tested conditions) dangerous temperatures that could damage the compressor.

Fig. 9. Discharge temperature increase due to the IHX adoption.

5. Conclusions

This paper presents a drop-in analysis of an internal heat exchanger used in a monitored vapour compression system. The fluids compared are R134a and two of its alternatives: R1234ze and R450A (R134a/R1234ze commercial mixture). The evaporation temperatures performed are 260K, 270K and 280K and the condensation temperatures are 300K, 310K, 320K and 330K. The main conclusions of the work are the following.

The cooling capacity increase obtained is higher at high compression rates (particularly for R1234ze), produced by a greater refrigerating effect increase than a mass flow decrease. The power consumption diminishes to a small degree. Consequently, the COP is increased using IHX for all refrigerants, being the greater augmentations produced by the alternatives, R1234ze and R450A. This effect is well predicted by the Aprea's and Domanski's criterions even though the Klein's criterion underpredicts the results.

Regarding to other IHX effects on refrigeration system, pressure drops of alternatives are below that of R134a and the same happens to discharge temperature difference. So, the disadvantages produced by the IHX introduction are less detrimental using R1234ze and R450A.

According to the results obtained from the study, it can be concluded that IHX produce benefits for all refrigerants tested and can be considered its use for R450A as drop-in or retrofit R134a replacement and new design installations using R1234ze. If the alternatives are used with IHX in a system that operates with R134a without it, R450A would overcome the R134a COP results but for R1234ze more system modifications would be necessary.

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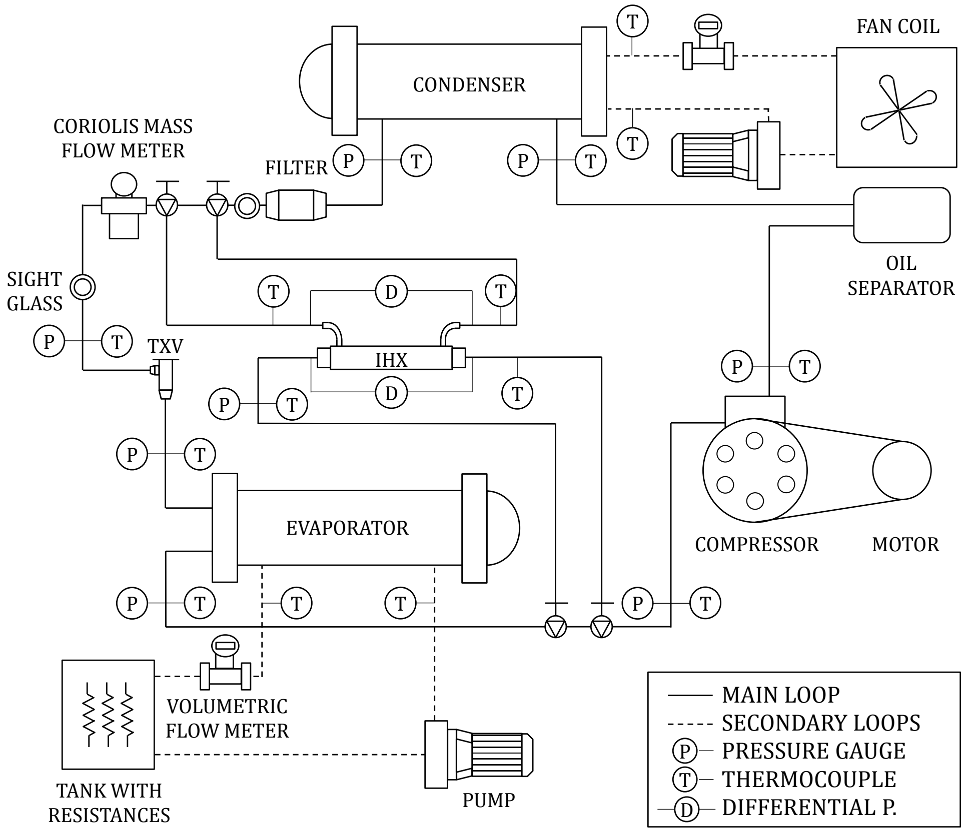
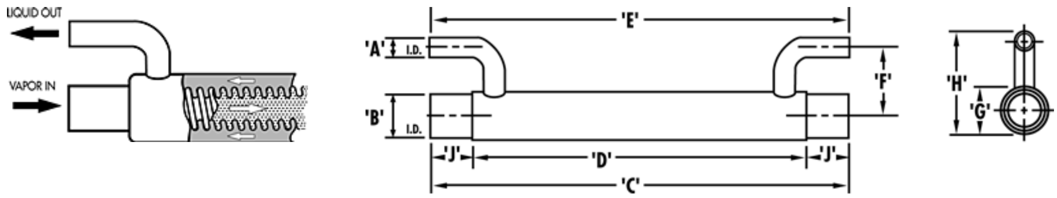


a)



	A	B	C	D	E	F	G	H	I
L (mm)	15.9	34.9	361.9	279.4	361.9	60.3	41.3	90.5	41.3

b)

Fig. 1. Schematic diagram of a) the test bench and b) the internal heat exchanger.

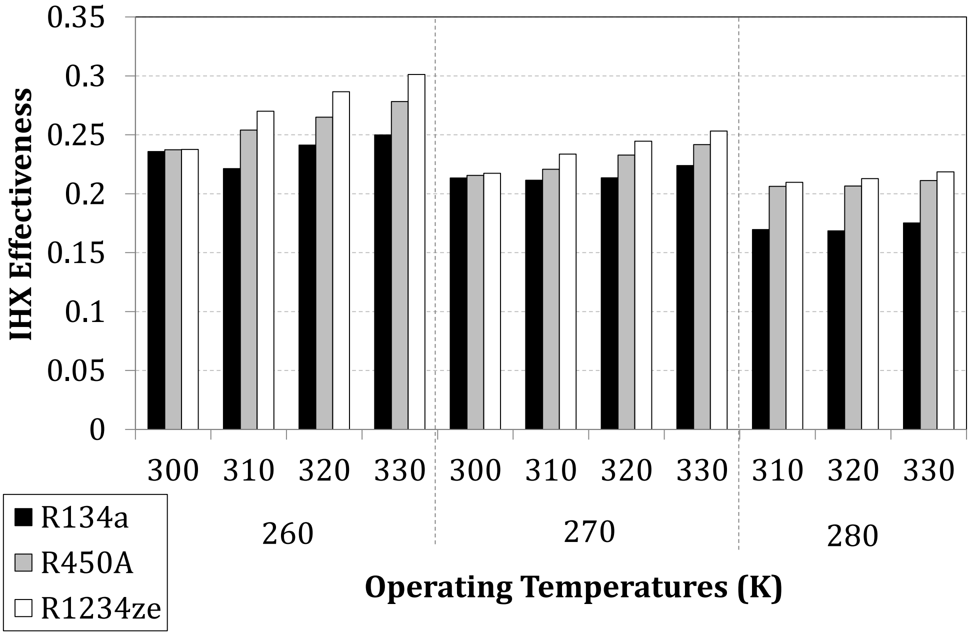


Fig. 2. Internal heat exchanger effectiveness.

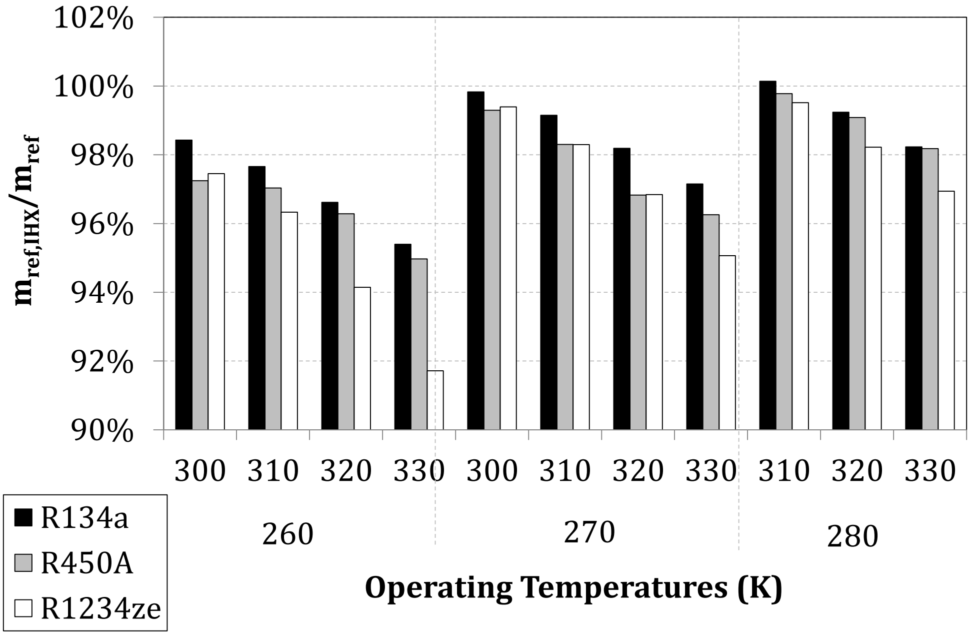


Fig. 3. Mass flow rate relative variations due to the IHX adoption.

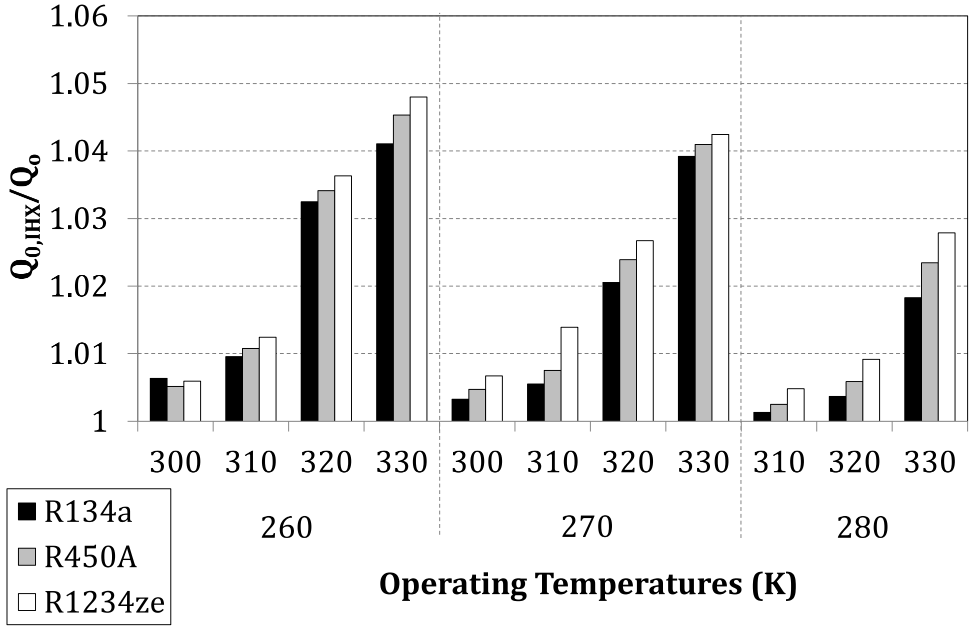


Fig. 4. Cooling capacity relative variations due to the IHX adoption.

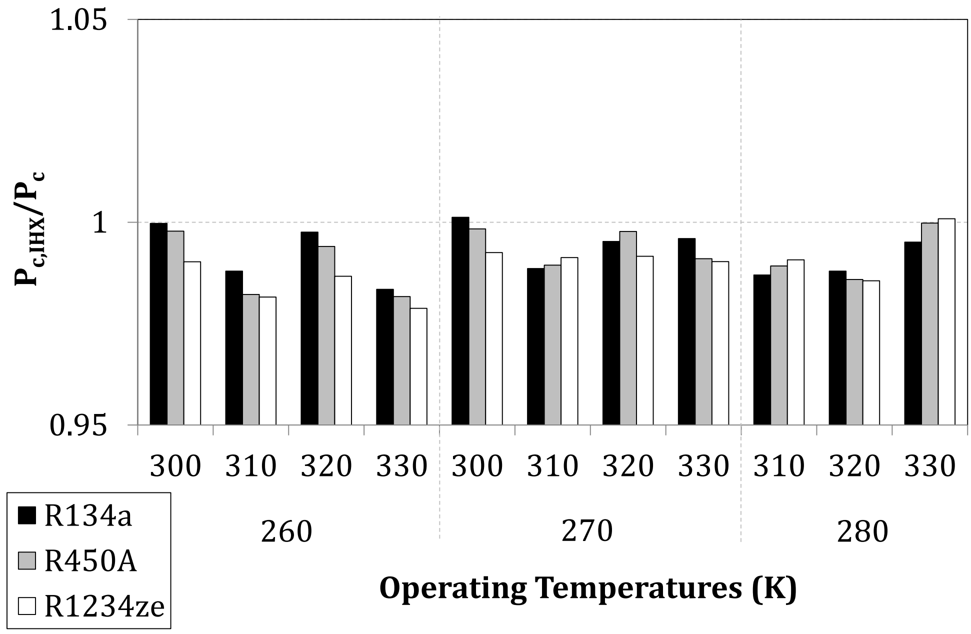


Fig. 5. Power input to the motor relative variations due to the IHX adoption.

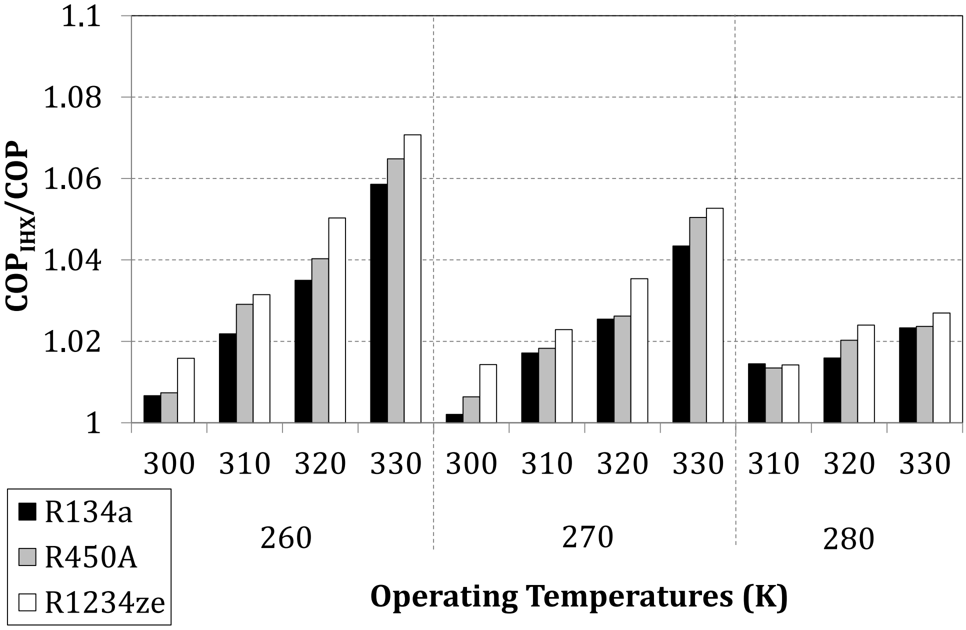


Fig. 6. COP relative variations due to the IHX adoption.

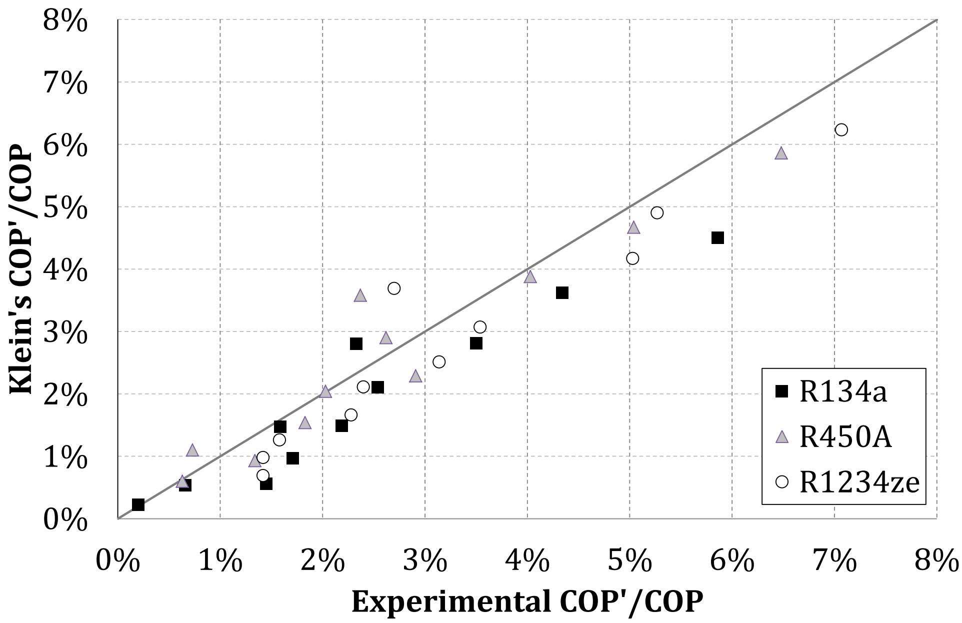


Fig. 7. Experimental COP relative variations versus Klein's predictions.

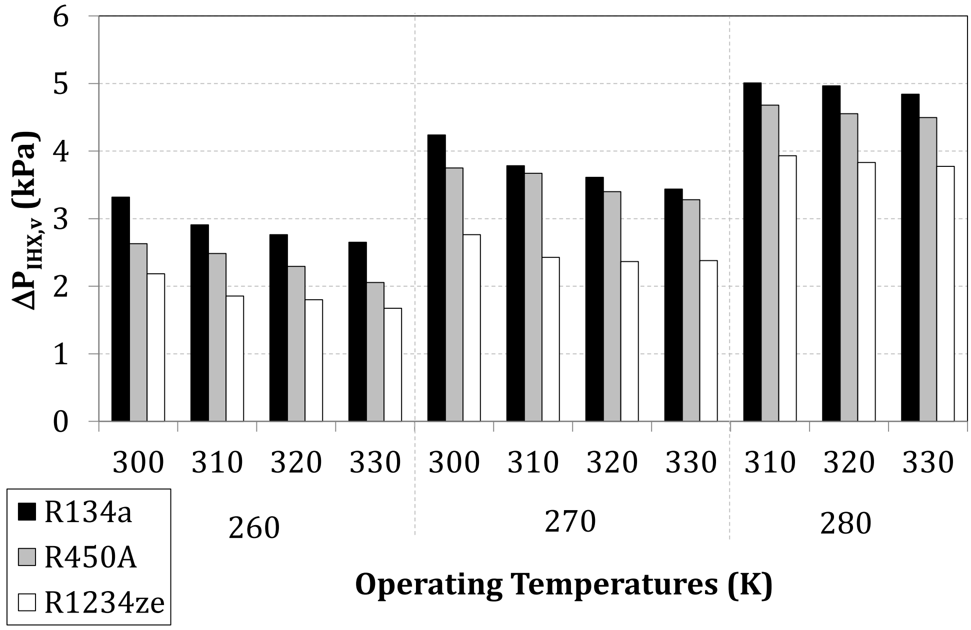


Fig. 8. Pressure drops at the vapour side of the IHX.

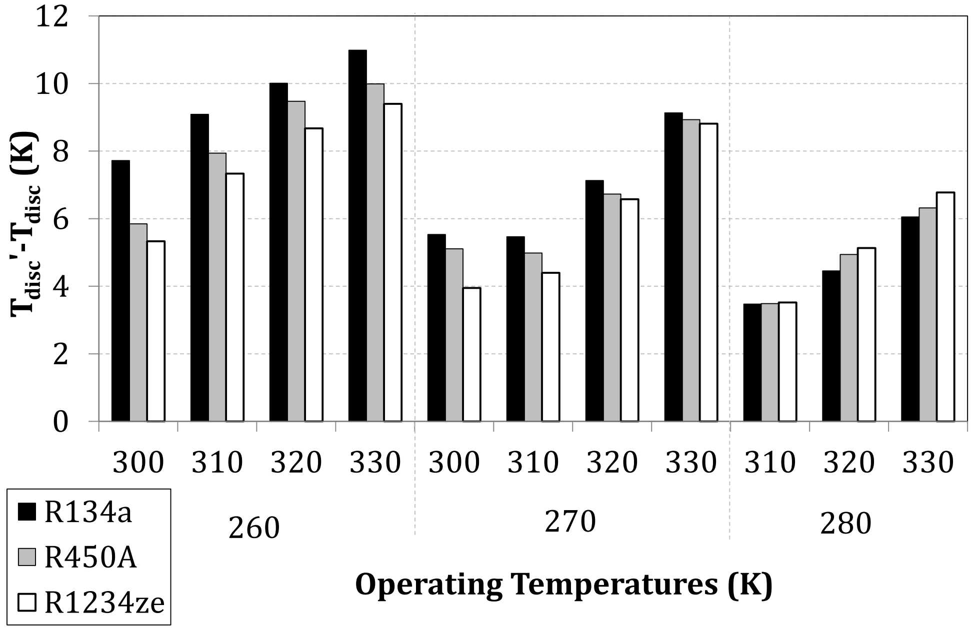


Fig. 9. Discharge temperature increase due to the IHX adoption.

FIGURE CAPTIONS

Fig. 1. Schematic diagram of a) the test bench and b) the internal heat exchanger.

Fig. 2. Internal heat exchanger effectiveness.

Fig. 3. Mass flow rate variations due to the IHX adoption.

Fig. 4. Cooling capacity relative variations due to the IHX adoption.

Fig. 5. Power input to the motor relative variations due to the IHX adoption.

Fig. 6. COP relative variations due to the IHX adoption.

Fig. 7. Experimental COP relative variations versus Klein’s predictions.

Fig. 8. Pressure drops at the vapour side of the IHX.

Fig. 9. Discharge temperature increase due to the IHX adoption.

Table 1. Measured parameters and equipment uncertainty.

Measured parameters	**Sensor**	**Reading Uncertainty**
Temperatures	K-type thermocouples	±0.3K
Pressures	Piezoelectric pressure transducers	±7kPa
Mass flow rate	Coriolis mass flow meter	±0.22%
Power input to the motor	Digital wattmeter	±0.15%
Compressor rotation speed	Capacitive sensor	±1%
Pressure drops in the IHX	Differential pressure transducers	±0.01kPa

Table 2. Mean operating parameters difference between test with IHX and test without IHX.

	Test conditions		Difference		
	T_o(K)	T_k(K)	T_o(K)	T_k(K)	$TSHD$(K)
R134a	260	300	0.10	0.18	-0.58
	260	310	-0.14	0.07	0.18
	260	320	0.14	0.27	0.12
	260	330	-0.23	0.07	-0.09
	270	300	-0.07	-0.56	-0.23
	270	310	-0.17	-0.10	-0.21
	270	320	-0.32	0.10	-0.04
	270	330	-0.28	0.03	-0.10
	280	310	-0.36	0.10	-0.08
	280	320	-0.10	-0.38	0.42
	280	330	-0.37	-0.11	-0.54
R1234ze	260	300	-0.31	-0.50	-0.11
	260	310	-0.33	-0.21	-0.55
	260	320	-0.15	-0.42	-0.18
	260	330	0.43	0.01	-0.58
	270	300	-0.07	0.10	-0.06
	270	310	-0.12	-0.11	-0.26
	270	320	-0.05	-0.07	-0.15
	270	330	-0.12	0.79	-0.01
	280	310	0.06	-0.70	-0.34
	280	320	-0.16	0.06	-0.20
	280	330	0.09	-0.01	0.16
R450A	260	300	-0.01	0.05	0.00
	260	310	-0.38	0.11	-0.25
	260	320	-0.07	0.02	0.13
	260	330	0.07	0.01	-0.44
	270	300	0.03	1.03	-0.04
	270	310	0.37	1.37	-0.38
	270	320	-0.06	-0.04	0.00
	270	330	0.15	0.02	0.12
	280	310	-0.78	-0.65	-1.16
	280	320	-0.39	-0.50	-0.60
	280	330	-0.13	0.14	0.11

Table 3. Summary of the main results uncertainty.

	T_o (K)	T_k (K)	$\dot{Q}_o$	COP
R134a	260	300	0.682%	0.832%
	260	310	0.741%	0.891%
	260	320	0.804%	0.954%
	260	330	0.878%	1.028%
	270	300	0.689%	0.839%
	270	310	0.697%	0.847%
	270	320	0.778%	0.928%
	270	330	0.857%	1.007%
	280	310	0.694%	0.844%
	280	320	0.722%	0.872%
	280	330	0.813%	0.963%
R1234ze	260	300	0.689%	0.839%
	260	310	0.753%	0.903%
	260	320	0.813%	0.963%
	260	330	0.883%	1.033%
	270	300	0.681%	0.831%
	270	310	0.733%	0.883%
	270	320	0.790%	0.940%
	270	330	0.865%	1.015%
	280	310	0.709%	0.859%
	280	320	0.771%	0.921%
	280	330	0.849%	0.999%
R450A	260	300	0.698%	0.848%
	260	310	0.765%	0.915%
	260	320	0.835%	0.985%
	260	330	0.922%	1.072%
	270	300	0.691%	0.841%
	270	310	0.730%	0.880%
	270	320	0.817%	0.967%
	270	330	0.908%	1.058%
	280	310	0.723%	0.873%
	280	320	0.788%	0.938%
	280	330	0.880%	1.030%

Table 4. Comparison between Aprea's [26], Domanski's [25] and Klein's [27] criteria and the experimental (COP'/COP) results.

	T_o (K)	T_k (K)	**Experimental Results**	**Aprea's criterion**	**Domanski's criterion**	**Klein's criterion**
R134a	260	300	+0.66%	+	+	+0.53%
	260	310	+2.19%	+	+	+1.49%
	260	320	+3.50%	+	+	+2.81%
	260	330	+5.86%	+	+	+4.50%
	270	300	+0.20%	+	+	+0.22%
	270	310	+1.71%	+	+	+0.97%
	270	320	+2.54%	+	+	+2.10%
	270	330	+4.34%	+	+	+3.62%
	280	310	+1.45%	+	+	+0.56%
	280	320	+1.59%	+	+	+1.47%
	280	330	+2.33%	+	+	+2.80%
R1234ze	260	300	+1.58%	+	+	+1.26%
	260	310	+3.14%	+	+	+2.51%
	260	320	+5.03%	+	+	+4.17%
	260	330	+7.07%	+	+	+6.23%
	270	300	+1.42%	+	+	+0.69%
	270	310	+2.28%	+	+	+1.66%
	270	320	+3.54%	+	+	+3.07%
	270	330	+5.27%	+	+	+4.90%
	280	310	+1.42%	+	+	+0.98%
	280	320	+2.40%	+	+	+2.11%
	280	330	+2.70%	+	+	+3.69%
R450A	260	300	+0.73%	+	+	+1.10%
	260	310	+2.91%	+	+	+2.29%
	260	320	+4.03%	+	+	+3.88%
	260	330	+6.48%	+	+	+5.86%
	270	300	+0.63%	+	+	+0.60%
	270	310	+1.83%	+	+	+1.54%
	270	320	+2.62%	+	+	+2.90%
	270	330	+5.04%	+	+	+4.67%
	280	310	+1.34%	+	+	+0.93%
	280	320	+2.03%	+	+	+2.04%
	280	330	+2.37%	+	+	+3.58%