Experimental evaluation of system modifications to increase R1234ze(E) cooling capacity

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Abstract

The GWP limitations are being progressively introduced in Europe through Regulation EU No 517/201, phasing out R134a in most of its refrigeration and air conditioning applications. Pure hydrofluoroolefins are proposed to substitute this fluid, however generally system modifications are needed to achieve a good performance. In the case of R1234ze(E), the cooling capacity is always much below that of R134a in drop-in or light retrofit substitutions.

This work performs an experimental comparison using R1234ze(E) and R134a under different refrigeration operating conditions. R1234ze(E) is tested considering the use or not of an internal heat exchanger, and R134a at the same or lower compressor rotation speed. Results show that the use of R1234ze(E) with an open-type compressor 43% larger and an internal heat exchanger of 25% effectiveness, leads to a cooling capacity augmentation, enough to reach R134a cooling capacity in the different conditions tested. For R450A, it is sufficient only with the IHX activation.

Keywords: variable speed compressor, internal heat exchanger (IHX), R1234ze(E), R134a, low GWP, cooling capacity.

Nomenclature

h	specific enthalpy (kJ kg^{-1})

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$\dot{m}_{ref}$	refrigerant mass flow rate (kg s^{-1})
N	compressor rotation speed (rev^{-1})
$\dot{Q}_o$	cooling capacity (kW)
SHD	superheating degree (K)
V_G	compressor geometric volume (m^3)
T	temperature (K)
Greek	
ρ_{suc}	suction density (kg m^{-3})
Subscripts	
in	inlet
o	evaporator, evaporating
out	outlet
k	condenser, condensing
Abbreviations	
GWP	Global Warming Potential
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HVACR	refrigeration, heating ventilation and air conditioning
IHX	internal heat exchanger
TXV	thermostatic expansion valve

1. Introduction

Refrigeration and air conditioning systems (HVACR) contribute to greenhouse effect by direct and indirect emissions [1]. Thus, direct emissions are related to leakages of hydrofluorocarbon (HFC) refrigerants (as a matter of fact, in 2010, 55% of global HFC consumed was used in HVACR systems [2]) and indirect emissions of CO_2 are caused by burning of fossil fuels to provide the electrical energy that these systems require.

By 2050, HFC CO_2-eq emissions will represent between 6% and 9% of global CO_2 emissions, which corresponds to 12–24% of the increase from business-as-usual CO_2 emissions from 2015 to 2050 [3]. R134a, with global warming potential (GWP) of 1300, is one of the most important HFCs consumed in developed countries and its use is increasing in developing countries [4], as shown in Table 1 [5].

Table 1. R134a relative consumption in different developing countries [5].

In recent years, several environmental protection policies are being approved to achieve a significant reduction of CO_2 equivalent emissions. Some of these regulations limit higher GWP HFC usage in HVACR systems, as EU No 517/2014 [6]. So, environmentally friendly refrigerants are becoming more and more interesting as HFC alternatives [7].

Two broad streams have emerged the last decade but any option meets all the desirable properties. On the one hand, 'natural' refrigerants (highlighting carbon dioxide, ammonia and hydrocarbons) [8] present very low GWP values but are not compatible with existing HFC systems (material and oil compatibility, security concerns, operating range, etc.). On the other hand, lower GWP HFCs, hydrofluoroolefins (HFOs) and new synthetic mixtures (HFC and HFO) offers easier substitution [7].

HFOs (GWP below 1) have sparked interest in the last years and many researches have appeared about the two most promising ones, R1234yf and R1234ze(E) [9]. R1234ze(E) offers some advantages as HVACR systems working fluid in comparison with R1234yf [10]:

- Although both fluids are classified as low flammable and non-toxic (A2L) by Standard ASHRAE 34, R1234ze(E) seems to be less flammable than R1234yf (or even non-flammable at specific humidity and temperature conditions) [11].
- Unlike R1234yf, R1234ze(E) two-phase heat transfer coefficient is similar to that of R134a for some geometries and operating conditions [10].

Previous experimental studies have confirmed that R1234ze(E) cooling capacity is much below that of R134a and it cannot be considered as drop-in or light replacement. Sethi et al. [9] estimated 25% lower R1234ze(E) cooling capacity in a vending machine with system modifications to match energy performance. Mota-Babiloni et al. [12] obtained 30% lower average cooling capacity in a medium capacity vapor compression system test bench. Drop-in cooling capacity presented by R1234ze(E) in the experimental study of Jankovic et al. [13] was 27% lower under equal evaporation and condensation temperatures.

Therefore, R1234ze(E) (or R1234yf) mixtures with HFC can be a good option [14]. However, while HFC/HFO blends show very similar properties and performance values to R134a, their GWP values are not low enough (about 600). Thus, in order to reach a large GWP reduction, pure R1234ze(E) should be considered.

R1234ze(E) can be used in R134a applications either in new design systems or applying major modifications to it (more cost-effective solution). Internal heat exchanger (IHX) can slightly enlarge R1234ze(E) cooling capacity and energy efficiency [15, 16]. Besides, regarding the good R1234ze(E) performance, some studies recommend a compressor enlargement to achieve similar cooling capacity than R134a [17].

Thus, this paper experimentally explores some system modifications in order to enlarge R1234ze(E) cooling capacity, allowing to match that of R134a. To meet this objective, a fully instrumented vapor compression test bench is run in a wide range of operating conditions. The test bench includes an open-type alternative compressor driven by a variable frequency drive and an IHX with bypass possibility.

The rest of the paper is organized as follows: In section 2, a brief thermodynamic overview that analyzes lower R1234ze(E) cooling capacity is performed. Later, section 3 detailed presents the experimental procedure. Then, in section 4, experimental results are presented and discussed. Finally, in section 5, the conclusions of the study are summarized.

2. Thermodynamic overview

The thermophysical properties of R134a and R1234ze(E), highlighting greatest differences between both refrigerants, are shown in Table 2. It should be noted that both vapor density and latent heat of R1234ze(E) are 19% and 7% lower than that of R134a, having a great influence on the cooling capacity.

Table 2. Main thermophysical differences between R134a and R1234ze(E) [14].

The cooling capacity ($\dot{Q}_o$) is defined as the product of the refrigerant mass flow rate ($\dot{m}_{ref}$) and the evaporator enthalpy difference (also known as refrigerating effect), Equation (1).

$$\dot{Q}_o = \dot{m}_{ref}\ (h_{out} - h_{in})_o \tag{1}$$

Mass flow rate depends on the compressor geometric and operating characteristics, suction conditions and the volumetric efficiency [18], Equation 2.

$$\dot{m}_{ref,} = \eta_v \rho_{suction} V_G \left(\frac{N}{60}\right) \quad (2)$$

So, if replacement suction density is much lower than the existing refrigerant (Figure 1) at similar operating conditions, either the compressor volumetric geometry (performing a compressor replacement) or the compressor rotation speed (using a frequency inverter) should be modified.

Figure 1. Suction density of a theoretical basic cycle: No pressure drops, SHD=7K.

3. Experimental procedure

3.1. Experimental setup

Several experimental tests are carried out in a vapor compression setup designed to simulate typical operating refrigeration and air conditioning conditions. The test bench consists of a main circuit and two secondary circuits, used to set the operating conditions. The experimental setup scheme is shown in Figure 2, which includes also the position of the thermocouples and pressure sensors.

Figure 2. Experimental setup scheme.

The main components of the vapor compression circuit are as follows:

- An open-type compressor, driven by a 5.5kW variable frequency drive. The compressor main characteristics are included in Table 3.
- R134a thermostatic expansion valve (TXV).
- A shell-and-tube condenser (1-2), with an external thermal exchange area of 2.87 m^2 where the refrigerant flows inside the shell and the secondary fluid across the tubes.
- An isolated counterflow tube-in-tube IHX. The geometrical characteristics are presented in Figure 3.
- And an isolated shell-and-micro-fin tube evaporator (1-2), with an external thermal exchange area of 1.81 m^2 where the refrigerant flows across the microfinned tubes and the secondary fluid along the shell.

Table 3. Main characteristics of the used compressor.

Figure 3. Geometrical characteristics of the IHX.

The secondary circuits (discontinuous line in Figure 2) allow setting a wide range of evaporating and condensing conditions and they consist of the heat load and the heat removal circuit.

- The heat load circuit is formed by a set of electrical resistances immersed in an isolated tank and a variable frequency pump, being the fluid employed a water–propylene glycol brine.
- The heat removal circuit, using water as secondary fluid, consists of a dry cooler with a variable-speed fan and a chiller.

The test bench is fully instrumented and all the relevant parameters are measured and monitored using a Personal Computer that receives the sensors information collected by the Data Acquisition System. Details about the sensors employed are given in Table 4 and as aforementioned; their location can be seen in Figure 2.

Table 4. Measured parameters and equipment uncertainty.

3.2. Tests conditions

In order to perform a complete assessment of the cooling capacity enhancement in the R1234ze(E) refrigeration system, 44 steady-state tests (22 with each refrigerant) are carried out varying the following operating conditions:

- Condensation temperature (T_k): [300-330] K. (medium evaporation conditions).
- Evaporation temperature (T_o): [260-280] K (from low to high ambient temperature, or winter/summer ambient conditions).

The superheating degree at the evaporator outlet is fixed at 7±1K by the TXV (the TXV screw was adjusted when R1234ze(E) is used) and the subcooling degree at the condenser outlet is of2K at intermediate conditions. The refrigerants purity is guaranteed by the supplier.

To calculate the cooling capacity (as shown in Equation 1), the refrigerant mass flow rate is directly measured from the installation (using a Coriolis flow meter) and the specific enthalpies are obtained from REFPROP 9.1 database [19], using the measurements of thermocouples and pressure sensors located at the inlet of the TXV (the expansion process is considered isenthalpic) and the outlet of the evaporator.

3.3. Cases studied

Theoretically (no pressure drops, no heat exchange to the ambient) and considering the operating conditions mentioned in the previous section, R1234ze(E) can match R134a cooling capacity with a compressor rotation speed or geometric volume approximately 36% higher than that of R134a, as shown in Table 5.

Table 5. Relative cooling capacity of R1234ze(E) compared to R134a

So, R1234ze(E) and R134a are compared experimentally, varying the compressor rotation speed (through the compressor variable frequency drive). Furthermore, variation of compressor rotation speed and the IHX activation (when using R1234ze(E)) have also been combined in order to investigate the compressor rotation speed reduction required. Table 6 summarizes the cases experimentally tested.

Table 6. Cases studied in the present work.

4. Results and discussion

This section shows the results obtained in the tests performed in the experimental setup, following the procedure presented in the previous section. The parameters studied in detail in this work are mass flow rate and cooling capacity. The results are shown in terms of relative deviation of R1234ze(E) from R134a, Equation 3 and 4.

$$\%\dot{m}_{ref} = \left(\frac{\dot{m}_{ref\,R1234ze(E)} - \dot{m}_{ref\,R134a}}{\dot{m}_{ref\,R134a}}\right) \cdot 100 \tag{3}$$

$$\%\dot{Q}_o = \left(\frac{\dot{Q}_{o\,R1234ze\,(E)} - \dot{Q}_{o\,R134a}}{\dot{Q}_{o\,R134a}}\right) \cdot 100 \tag{4}$$

It must be noted that this work only focuses on mass flow rate and cooling capacity. Additional information about experimental comparisons of COP performed by R1234ze(E) and R134a without system modifications can be found in [9, 12, 13]. In [16], Mota-Babiloni et al. shows an enlargement of R1234ze(E) COP between 2 and 7% when the IHX is used. Besides, Brasz [17] has proved that there is an increase on energy efficiency between 4 and 4.5% if a higher compressor is used with R1234ze(E) instead of R134a (2% of that due to higher compressor).

4.1. Results adjusting the TXV

In the first case studied, both refrigerants are tested without IHX and at the same compressor rotation speed. This refrigerant replacement can be considered a light retrofit because the only modification is the TXV adjustment to set the evaporator superheating degree at 7K (if feasible it would present the lowest cost). This case is considered the base for further comparisons.

Figure 4 contains the relative deviations of mass flow rate and cooling capacity between R1234ze(E) and R134a. As it is depicted from before, the R1234ze(E) mass flow rate results much below than that of R134a (between 18% and 29%). Thus, considering also the lower R1234ze(E) refrigerating effect, leads to a strong R1234ze(E) cooling capacity reduction (between 22% and 34%); that in fact it is higher than expected (up to 28%).

Figure 4. Case 1 relative deviation a) mass flow rate and b) cooling capacity.

The differences observed with this modification would make the R1234ze(E) unusable as drop-in or light retrofit replacement for R134a systems.

4.2. Retrofit including IHX

Results from the addition of an IHX, with a 25% average effectiveness using R1234ze(E), to the basic vapor compression cycle. This case can still be considered a light retrofit replacement, as the modification is not very expensive (inclusion of a countercurrent liquid-vapor heat exchanger).

The IHX affects differently to the two parameters that influences the system cooling capacity: reduction of mass flow rate (additional pressure drop and superheating in compressor suction) and increase of refrigerating effect (by the increase of evaporator enthalpy difference). The final effect on the cooling capacity will depend on the magnitude of both modifications.

Again, mass flow rate and cooling capacity relative deviations are presented, Figure 5. The R1234ze(E) mass flow rate relative deviation is lowered at values between 20% and 33%, by the extra pressure losses introduced by the IHX and the diminution of the suction density (by the additional superheating, between 4 and 13K). However, the reduction of mass flow rate is not reflected in the cooling capacity, due to the greater refrigerating effect increase (average inlet vapor quality passes from 0.31 to 0.27). Hence, the resulting R1234ze(E) cooling capacity reduction is comprised between 21% and 31% (IHX has greater influence at higher compression ratios). As was presented in [16] that uses the same this experimental setup, the pressure drops at the vapor side of the IHX when R1234ze(E) is used are comprised around 2kPa at lower evaporating temperatures and below 4kPa at higher ones.

Figure 5. Case 2 relative deviation a) mass flow rate and b) cooling capacity.

Even though the R1234ze(E) cooling capacity reduction is minor than the base case thanks to a slight system modification, this change is not enough to recommend R1234ze(E) as refrigerant alternative in R134a systems.

4.3. Retrofit varying compressor rotation speed

The third case studied considers the variation of compressor rotation speed using a frequency inverter, which drives the motor-compressor ensemble. Frequency inverters are commonly used in part load applications [20]. Besides this devices can be added to the vapour compression system to increase the compressor rotation speed and hence, the mass flow rate and cooling capacity.

In this case the compressor speed is adjusted in order to obtain similar refrigerant mass flow rate using both refrigerants. So, the previous results using R1234ze(E) at 577.4 (±1.4) rpm are compared with experimental tests using R134a at lower compressor rotation speed. Although Table 5 depicted that R1234ze(E) operating at 36% higher compressor rotation speed than R134a can ideally match cooling capacity, it can be extracted from previous results (section 4.1.) that the required increase of mass flow rate (and therefore, compressor rotation speed) is higher due to different suction line pressure losses and the differences in volumetric efficiency using both refrigerants.

Experimental results obtained in the case that R1234ze(E) operates at 43% higher compressor rotation speed than R134a, 577.4 (±1.4) rpm using R1234ze(E) and 404.7(±1.5) rpm using R134a, is compared and shown in Figure 6. In this case, the R1234ze(E) mass flow rate overcomes the observed for R134a in all cases, being up to 5% higher. This similar mass flow rates values for R1234ze(E) and R134a are not enough for R1234ze(E) to match R134a cooling capacity. In the experimental tests it has been observed also a decrease below 2% in volumetric efficiency when R134a compressor rotation speed is 404.7 rpm.

Figure 6. Case 3 relative deviation a) mass flow rate and b) cooling capacity.

The increase of compressor rotation speed can also be seen as an enlargement of compressor swept volume of 43% for R1234ze(E) compared to R134a. And, as it has been demonstrated, it is not enough to match the R134a cooling capacity. So, the last comparison would include both retrofit solutions presented in this work, IHX inclusion and compressor substitution.

4.4. Retrofit varying compressor rotation speed and including IHX

The last case studied combines all the modifications included in the previous comparisons, including an IHX and adjusting the size of the compressor or the compressor rotation speed.

Figure 7 shows the results of the comparison. In this case, the mass flow rate is very similar to that of R134a, being the deviations obtained very small, either positive or negatives. The IHX slightly reduces the R1234ze(E) mass flow rate, but at the same time, the lowering of R134a compressor rotation speed is much greater, so both mass flow rates are almost the same.

Figure 7. Case 4 relative deviation a) mass flow rate and b) cooling capacity.

Finally, the R1234ze(E) cooling capacity is matched to that of R134a in this case. The combination of both system modifications makes their cooling capacity results very close (between -3 and 1% of deviation). It should be noted that as it has been observed before, best R1234ze(E) cooling capacity results are obtained at higher evaporation and condensation temperatures. However, this solution can be considered enough to introduce R1234ze(E) in

R134a systems without cooling capacity penalization at typical refrigeration and air conditioning operating conditions.

4.5. Brief consideration using R450A as alternative

As mentioned in introduction (section 1), the new synthetic mixtures offers great GWP reductions, even though, a priori, the environmental benefit is not comparable to that offered by pure HFOs. When R450A (GWP of 548) was compared to R134a, its cooling capacity values were similar [14], especially at great mass flow rates [21]. As those results were very close, these differences could be overcome with the sole introduction of a properly designed IHX, that increases the R450A cooling capacity up to 4% (at high condensation temperatures) [16].

5. Conclusions

Very low GWP refrigerants must be used in refrigeration and air conditioning systems with the aim of achieving significant reduction in direct CO_2-eq emissions. In this sense, restrictive regulations are being approved in most of developed countries. HFOs are very low GWP fluids that are being tested in recent years to be extended in near all HVACR applications. Among them, highlights R1234ze(E), with a GWP of 4 and less flammable than other synthetic replacement options.

In previous works it has been proved that R1234ze(E) is infeasible as direct replacement of R134a because of a much lower cooling capacity. This paper studies some retrofit (one minor modification, one major, and the combination of both) options to reduce cooling capacity difference between two fluids. The main conclusions of the work are as follows.

Only maintaining the superheating and subcooling degree at the same level, R1234ze(E) cooling capacity is much lower than that of R134a because of the lower mass flow rate (lower suction density and volumetric efficiency) and refrigerating effect (lower latent heat).

When the IHX is introduced in R1234ze(E) tests, the cooling capacity differences are reduced but still are greater than 20%. A great modification as a 43% compressor rotation speed enlargement matches mass flow rate of both fluids but leaves the cooling capacity still below.

To ensure similar cooling capacity results than R134a in a wide range of refrigeration operating conditions, R1234ze(E) could use a compressor 43% greater and an internal heat exchanger. This solution can offer great reductions in term of CO_2 equivalent emissions and is not exceedingly expensive if it is compared to a new design system.

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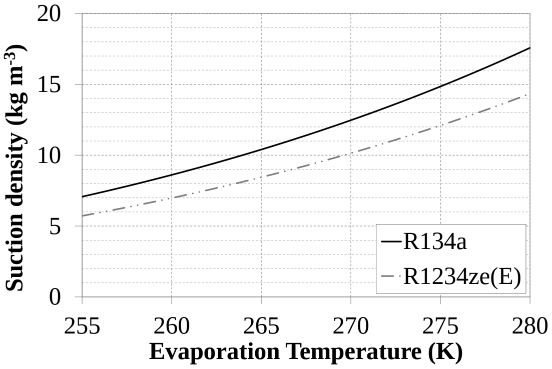


Figure 1. Suction density of a theoretical basic cycle: No pressure drops, SHD=7K.

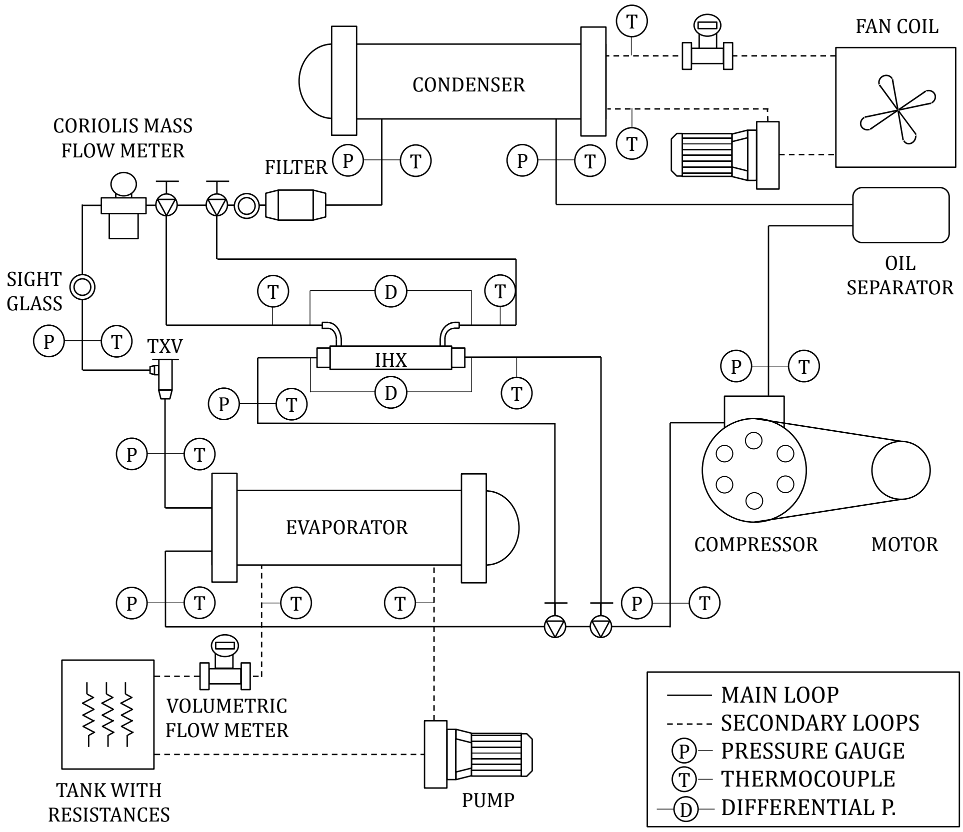
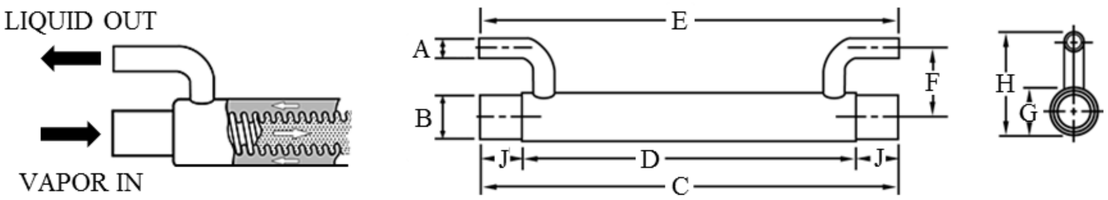
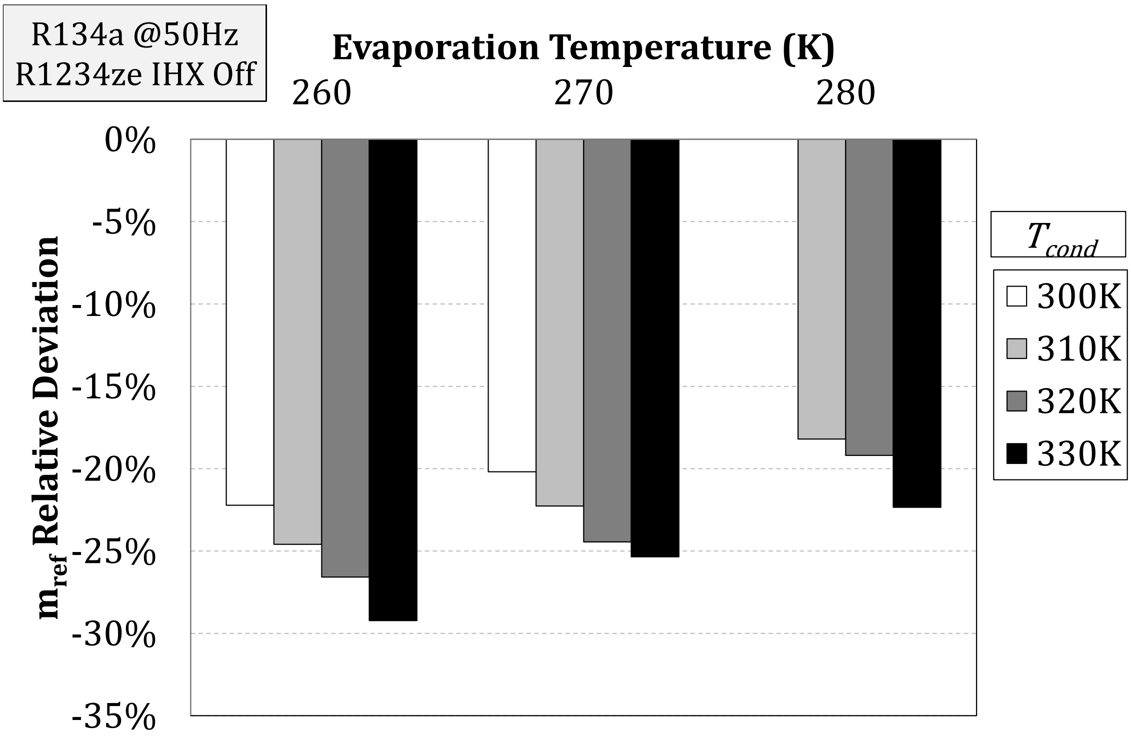


Figure 2. Schematic diagram of the test bench.



	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

Figure 3. Geometrical characteristics of the IHX.



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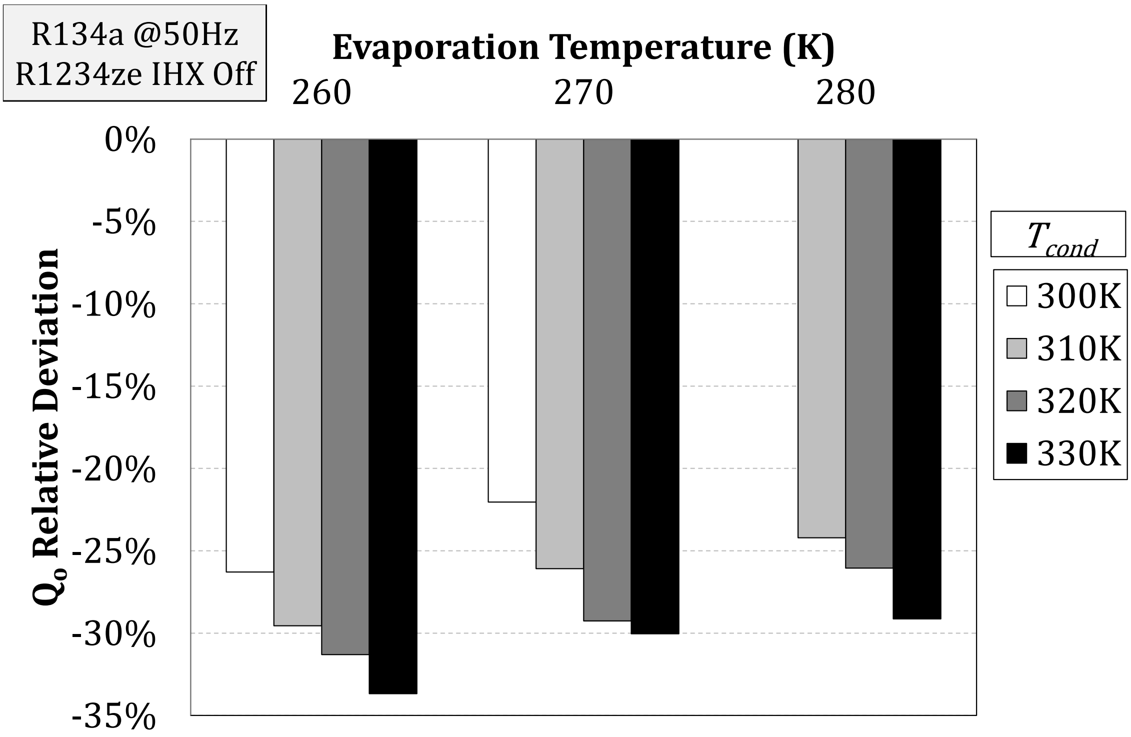

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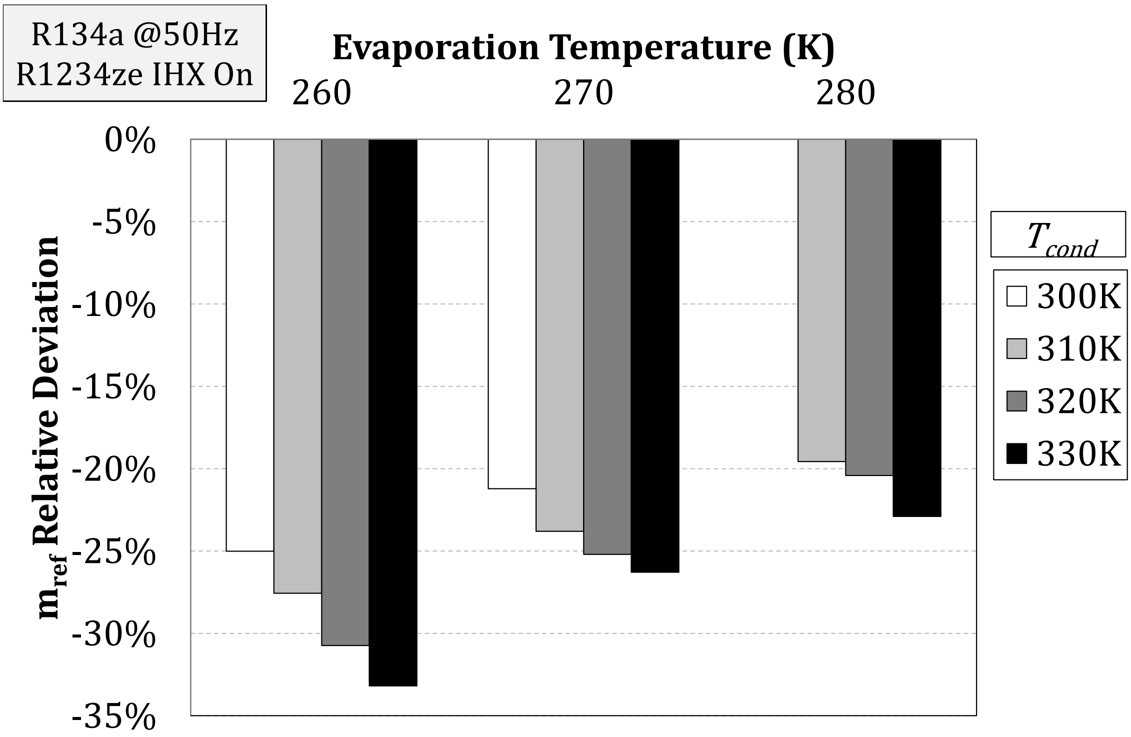
Figure 4. Case 1 relative deviation a) mass flow rate and b) cooling capacity.



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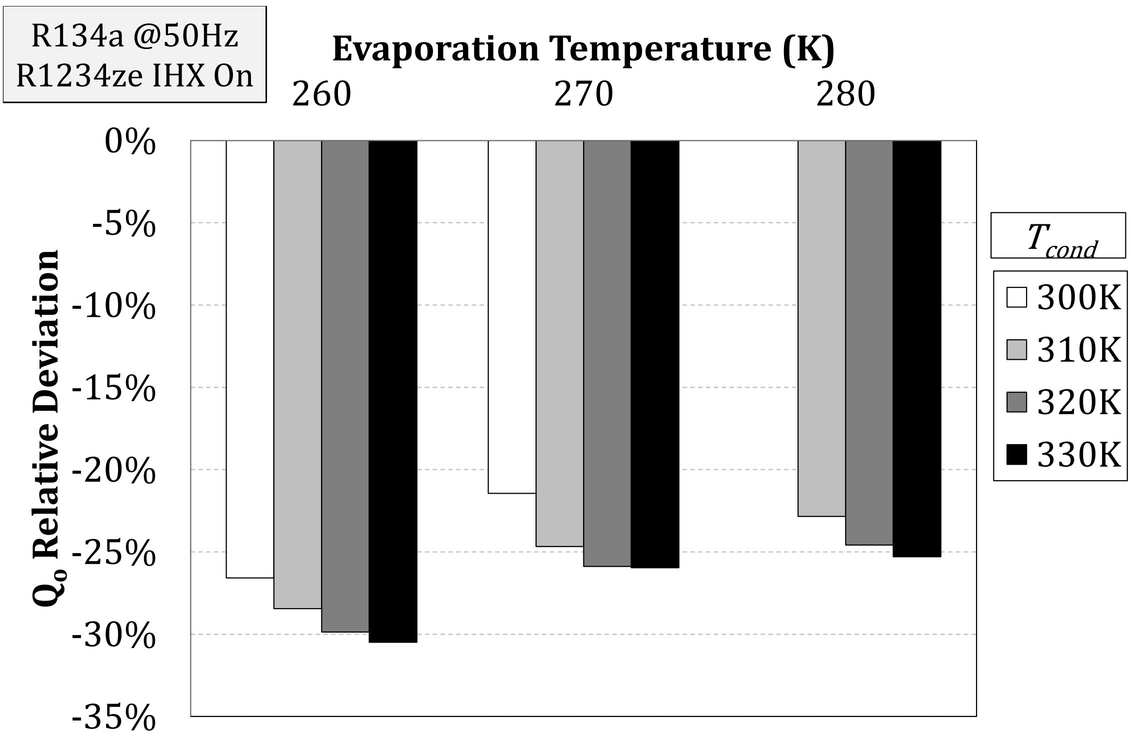
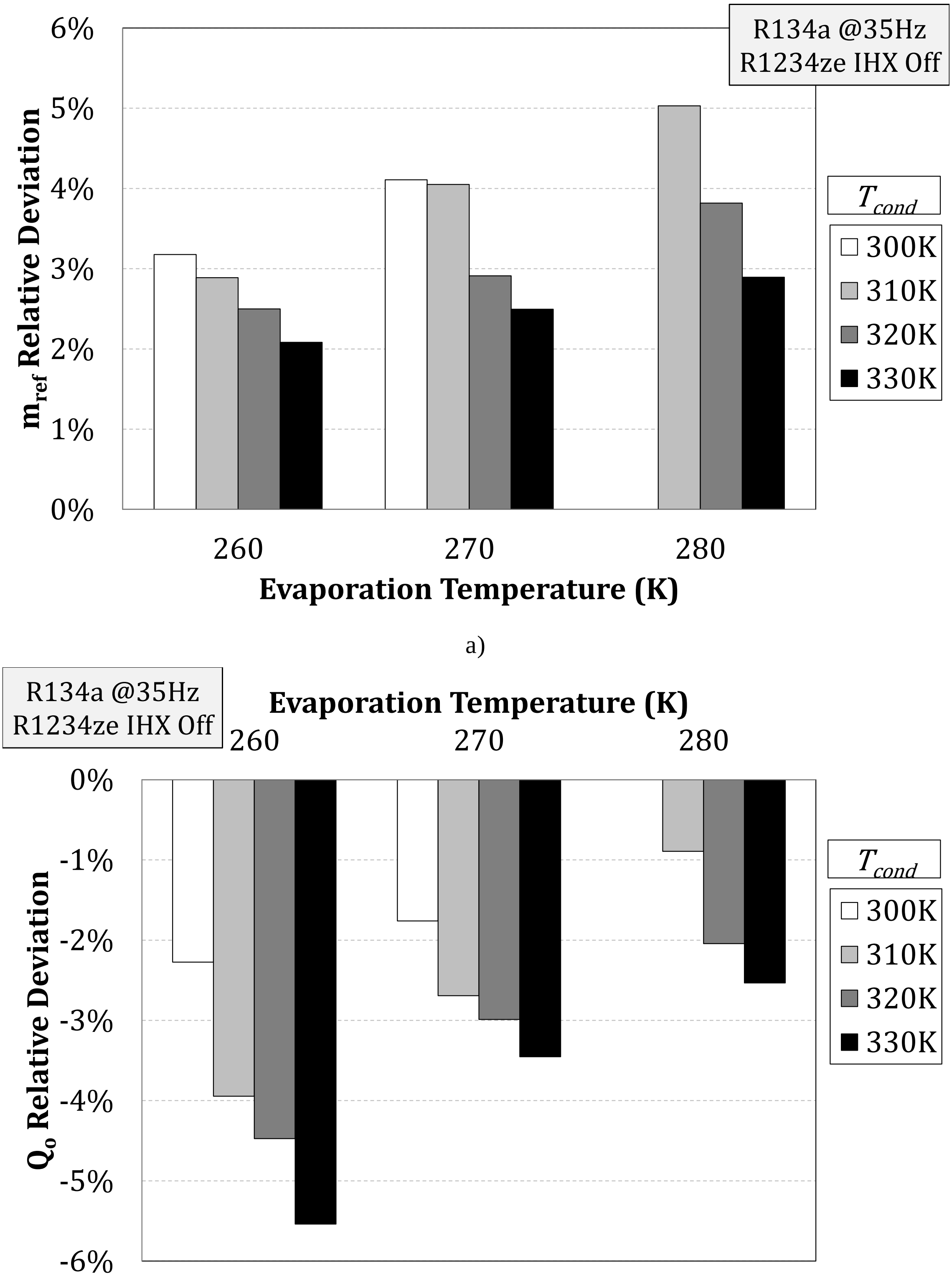


b)

Figure 5. Case 2 relative deviation a) mass flow rate and b) cooling capacity.



a)

b)

Figure 6. Case 3 relative deviation a) mass flow rate and b) cooling capacity.

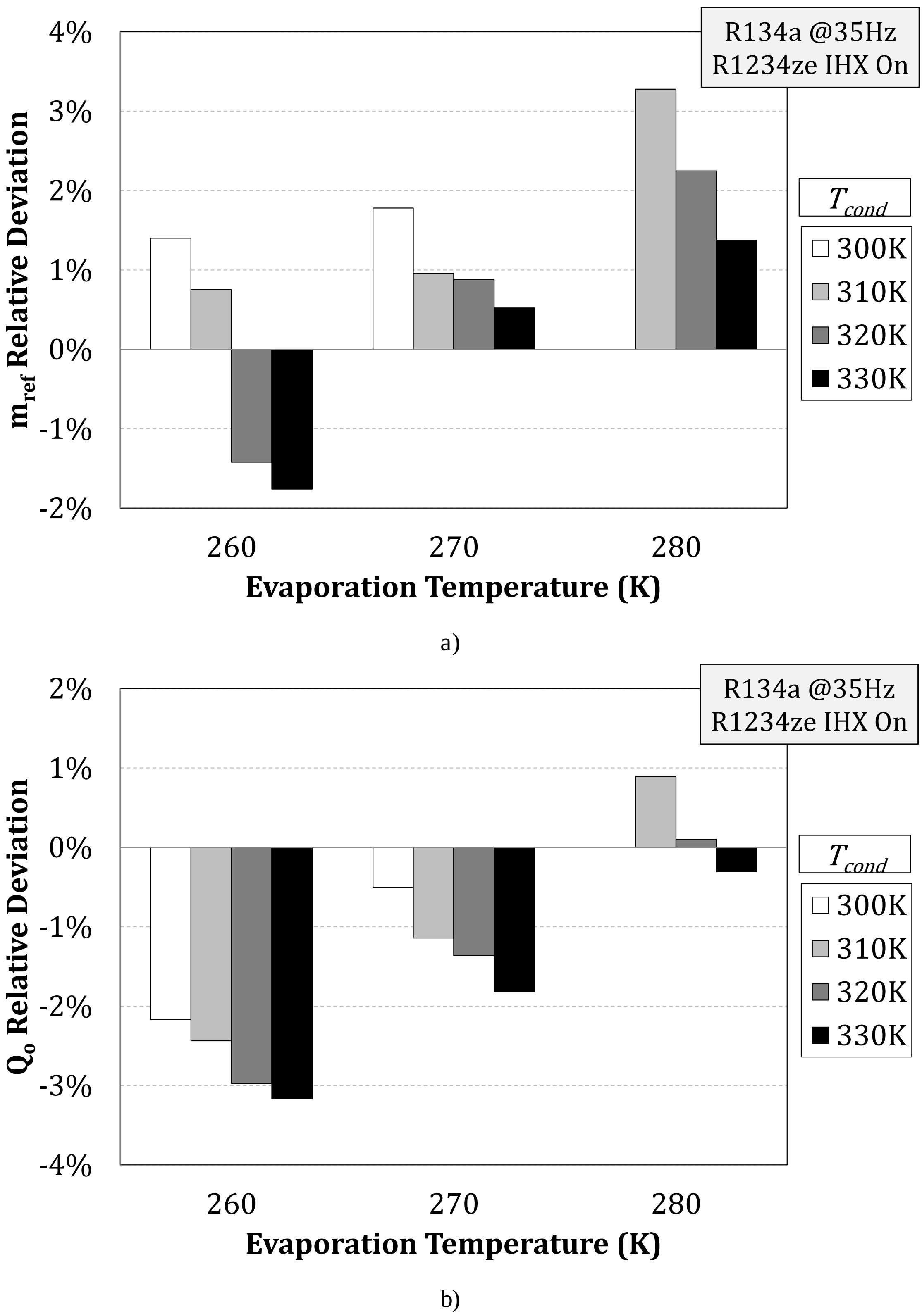


Figure 7. Case 4 relative deviation a) mass flow rate and b) cooling capacity.

FIGURE CAPTIONS

Figure 1. Suction density of a theoretical basic cycle: No pressure drops, SHD=7K.

Figure 2. Schematic diagram of the test bench.

Figure 3. Geometrical characteristics of the IHX.

Figure 4. Case 1 relative deviation a) mass flow rate and b) cooling capacity.

Figure 5. Case 2 relative deviation a) mass flow rate and b) cooling capacity.

Figure 6. Case 3 relative deviation a) mass flow rate and b) cooling capacity.

Figure 7. Case 4 relative deviation a) mass flow rate and b) cooling capacity.

Table1. R134a relative consumption in different developing countries [5].

Country	**Period**	**% of HFC consumption**
Chile	2008 to 2012	38%
Bangladesh	2013	93%
Ghana	2014	57%

Table2. Main thermophysical differences between R134a and R1234ze(E) [14].

	R134a	**R1234ze(E) (%reduction)**
Critical Pressure (kPa)	4059.28	3634.90 (-10%)
Vapour density[a] (kg m^{-3})	14.35	11.65 (-19%)
Liquid therm. cond.[a] (W m^{-1} K)	92.08	83.11 (-10%)
Latent heat (kJ kg^{-1})	198.72	184.28 (-7%)

Table 3. Main characteristics of the used compressor.

Parameter	Value
Motor pulley (m)	0.180
Cylinder number	2
Cylinder bore (m)	0.085
Cylinder stroke (m)	0.060
Oil type	POE BSE32
Oil charge (m^3)	0.025

Table 4. Measured parameters and equipment uncertainty.

Measured parameters	**Sensor**	**Uncertainty**
Temperatures	K-type thermocouples	±0.3K
Pressures	Piezoelectric pressure transducers	±7kPa
Mass flow rate	Coriolis mass flow meter	±0.22%
Compressor rotation speed	Capacitive sensor	±1%

Table 5. Relative cooling capacity of R1234ze(E) compared to R134a.

T_{evap}	T_{cond}	**R134a at 577rpm** **R1234ze(E) at 577rpm**	**R134a at 424rpm** **R1234ze(E) at 577rpm**
260	300	-26.4%	0.2%
260	310	-26.9%	-0.5%
260	320	-27.5%	-1.3%
260	330	-28.2%	-2.3%
270	300	-25.4%	1.5%
270	310	-25.8%	0.9%
270	320	-26.3%	0.3%
270	330	-26.8%	-0.4%
280	310	-24.7%	2.5%
280	320	-25.0%	2.0%
280	330	-25.4%	1.5%

Table 6. Cases studied in the present work.

Case	**R134a**		**R1234ze(E)**	
	IHX	Comp freq.	IHX	Comp freq.
1	No	50 Hz	No	50 Hz
2	No	50 Hz	Yes	50 Hz
3	No	35 Hz	No	50 Hz
4	No	35 Hz	Yes	50 Hz