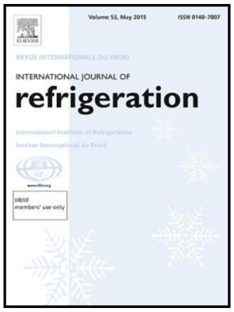

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Experimental study of R1234yf as a drop-in replacement for R134a in a domestic refrigerator

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Highlights

- An experimental study of R1234yf as a drop-in replacement for R134a is presented
- An alternative methodology was proposed to estimate the optimal mass charge
- R1234yf optimal charge was 92.2 g, about 7.8% lower than R134a
- A thermal and energy comparison between R134a and R1234yf was analyzed
- The TEWI analysis for the R1234yf was 1.13% higher than for R134a

Abstract

This paper presents an experimental study for three identical domestic refrigerators using R1234yf as a drop-in replacement for R134a. An alternative methodology was proposed to estimate the optimal mass charge for R1234yf; with the use of such methodology, new evidences were sought on the thermal behavior of the refrigerator compartments as well as at the heat exchangers. Additionally, energy performance for both refrigerants was measured, and, finally, a TEWI analysis was conducted. For the type of refrigerator evaluated, results showed that R1234yf presented an average (for the 3 refrigerators) of 0.4°C for the fresh food compartment, and 1.2°C for the freezer, among different charges with respect to R134a. The optimal charge for R1234yf was 92.2 g, which is about 7.8% lower than the one for R134a, which represents a small increase of 4% in energy consumption in comparison to R134a. Finally, the TEWI analysis for the R1234yf was 1.07% higher than the R134a.

Keywords: domestic refrigerator; R1234yf; drop-in; optimal charge; thermal analysis.

Nomenclature

COP	Coefficient of Performance
EC	Energy consumption [kWh yr^{-1}]
FF	Fresh food compartment
FZ	Freezer compartment
GWP	Global Warming Potential
L	Average annual refrigerant leakage [kg yr^{-1}]
m	Refrigerant charge [kg]
n	System life time [yr]
N_{cycles}	Number of cycles
ODP	Ozone Depletion Potential
P	Pressure [bar]
t	Time [min, h]
T	Temperature [°C]
TEWI	Total Equivalent Warming Impact [kg_{CO2}]

Greek symbol

α	Percentage of refrigerant recovered [%]
β	CO_2 emission factor [kg_{CO2} kWh^{-1}]

Subscripts

cond	Condenser
cycle	Total time
des	Discharge line

evap	Evaporator
int	Interpolation
OFF	Stop of the compressor
ON	Working of the compressor
suc	Suction line

1. Introduction

Over the last two decades, hydrofluorocarbon R134a has been the most important and dominant refrigerant for household appliances, air conditioning and chillers. However, this refrigerant has a high global warming potential, GWP, of approximately 1300, which contributes significantly for the greenhouse effect (Drake et al. 2011). As from January 2015, Europe's UE regulation N°517/2014 restricts the use of hydrofluorocarbons, HFCs, with a GWP of 150 or more (European Parliament and the Council, 2014). In this regard, it exists two important alternatives to replace the HFCs for refrigeration systems: natural refrigerants (CO_2, hydrocarbons and ammonia), and synthetic refrigerants. Each group of refrigerants presents advantages and drawbacks; for example, the use of hydrocarbons, HCs, offers a good drop-in replacement for halogenated refrigerants in terms of environmental impacts and energy consumption (Harby, 2017). In the field of domestic refrigeration, several studies have been carried out with HCs and mixtures of them to replace R134a (Wongwises and Chimres, 2005; Mohanraj et al. 2009; Liu et al. 2015). However, due to their high flammability, technical restrictions have been applied for its use in domestic refrigerators, from which its sales have been prohibited in several countries of Latin America, the USA, as well as in some Asian countries.

As an alternative to the HCs, R1234yf synthetic refrigerant from the family of the hydrofluoroolefins, HFOs, has emerged recently as a replacement fluid for R134a (Minor et al. 2010). Some of the main advantages of using R1234yf are its thermodynamic properties and its low level of toxicity. In addition, its ozone depletion potential, ODP, is zero, and its

GWP is 1 (Spatz and Minor 2008; Nielsen et al. 2007; Papadimitriou et al. 2008; Myhre et al. 2013).

Within specialized literature, some studies have analyze the feasibility of replacing R134a with R1234yf (Brown 2013; Kedzierski et al. 2015). Air conditioning systems working with R1234yf are the most widely studied; for example, Zilio et al. (2011) modified an automotive air conditioning to evaluate the performance between the refrigerants R1234yf and R134a. Experimental results indicated that, for a given cooling capacity, R1234yf systems presented a lower performance than the baseline R134a. However, such performance can be improved with some simple hardware modifications. Zhaogang Qi (2015) theoretically analyzed the coefficient of performance, COP, for the R1234yf compared to that of R134a for various operating conditions of the vehicle, he concluded that the COP for R1234yf was lower than that obtained with R134a. In addition, Cho and Park (2016), in order to evaluate both refrigerants, performed an exergy analysis for different compressor speeds in an automotive air conditioning system. The R1234yf system had a smaller cooling capacity and lower COP compared to the R134a system. In addition, the R1234yf system showed lower second law efficiency than the one of the R134a system at all compressor speeds. Ortega and Reis (2016) developed a compressor model for an air conditioning system which simulates the operation working with R1234yf, R134a and R290.

Other studies like Yataganbaba et al. (2015), studied two evaporator refrigeration cycles through a model based on an exergy analysis and they concluded that R1234yf and R1234ze were adequate alternatives to replace R134a. Boumaraf et al. (2014) proposed a novel ejector expansion refrigeration system, which compared R134a with its substitute R1234yf. Such studies showed significant improvement for both R134a and R1234yf. The increase in COP was higher for R1234yf at high condensing temperatures. Lawrence and Ebel (2014) experimentally evaluated the performance of two-phase ejectors and a two-phase ejector cycle with R1234yf and R134a, and they concluded that both fluids had obtained similar performance.

Other authors experimentally obtained viable operational ranges for R1234yf as a replacement for R134a, from which the energy parameters of the alternate refrigerant were very close to those of the R134a under high condensation temperatures and with the using of an internal heat exchanger (Navarro-Esbrí et al. 2013a; Navarro-Esbrí et al. 2013b; Mota-Babiloni et al. 2014). Jankovic et al. (2015) characterized and validated a low power refrigerating system, by assessing the performances for R1234yf, R1234ze(E) and R134a in different operational conditions. R1234yf showed that it is an adequate drop-in for R134a, but R1234ze(E) may perform better when an overridden compressor is used to match the refrigerant system cooling power.

Regarding the use of R1234yf in small capacity refrigeration systems, Yana Motta et al. (2010) presented experimental results for a vending machine, which operates with R1234yf, they evaluated its configuration for the liquid-suction heat exchanger, and concluded that the performance was very similar to that for R134a. Further, to this study, Sethi et al. (2016) analyzed both theoretically and experimentally a vending machine, which used R1234yf. They concluded that, based on actual drop-in system testing, the R1234yf showed capacity and efficiency similar to R134a. Karber et al. (2012) worked with two different refrigerators, one of them with basic technology and the other with more advanced technology. The authors used AHAM standard HRF-1 to evaluate and compare the energy performance among R1234yf, R1234ze and R134a. They concluded that R1234yf represented a maximum increment of 2.7% in the energy consumption, indicating that it is a suitable replacement for R134a. Righetti et al. (2015) performed a comparative study using the refrigerants R1234yf, R1234ze(E) and R600a within a roll-bond evaporator for domestic refrigerators and they concluded that R1234yf showed very similar performances to those for R134a. Aprea et al. (2016) experimentally evaluated a domestic refrigerator using R1234yf as a substitute for R134a. Their investigation was based on comparing the energy performance among both refrigerants under the UNI-ISO 15502 norm. In addition, through a pull-down test, they obtained an optimal charge of 10% higher than with R134a; such analysis was performed without any modification to the vapor-compression cycle. Recently, Aprea et al. (2017) presented another experimental analysis among R134a, R1234yf and refrigerant mixture of R134a/R1234yf (10/90% weight), which is used in domestic refrigerators. Their results showed that the refrigerant mixture was the best drop-in refrigerant for R134a. In addition, the mixture lead to a reduction in the electrical energy consumption during the pull-down tests of about 7.5 and 10% as compared to R134a and R1234yf, respectively.

Based on the above, R1234yf is shown as an ideal refrigerant to replace R134a. In most results, small increases in energy consumption were obtained when using R1234yf in comparison with R134a. Regarding the application of R1234yf in domestic refrigerators, it is worth to say that there is not enough information available, restricted to energy evaluation when comparing the conventional refrigerant R134a with R1234yf; these evaluations were performed under specific operational conditions and some of them with design modifications.

In order to continue and to extend previous studies on the field of household appliances, this paper presents the details of an experimental study for R1234yf as a drop-in replacement for refrigerant R134a in a domestic refrigerator with a 0.3 m^3 volumetric capacity. In this work, we emphasize the use of R1234yf, prioritizing the replacement of the refrigerant without making any modifications to the vapor compression system. As novel aspect to the reported studies in the area, we propose an alternative methodology to estimate the optimal mass charge for R1234yf, as well as the effects of the mass charge on some cycle parameters. In addition, thermal behaviors were analyzed along with the heat exchangers for both refrigerants. Furthermore, a comparison of temperatures for refrigerator compartments is performed with respect to the baseline (R134a). Finally, a total equivalent warming impact, TEWI, analysis is shown comparing both refrigerants.

2. Refrigeration system

The type of domestic refrigerator used in this study is designed to work with the refrigerant R134a. In contrast with the few published studies on domestic refrigeration evaluating R1234yf, in this study, tests for three identical domestic refrigerators were performed with the aim of presenting results with a higher degree of reliability. The volumetric capacity of the refrigerator is 0.3 m^3 and its external dimensions are 1.76m x 0.59m x 0.71m (height x width x length). Figure 1 shows the refrigerator, which is a top mount type with two main compartments: the freezer, FZ, located at the top, and the fresh food compartment, FF, located at the bottom. This refrigerator is a no-frost type (automatic defrost) and the air flow distribution is through forced convection. The details of the main components are shown in Table 1.

2.1 Test procedure

In this paper, the performance assessment for R1234yf is based on the determination of the optimal charge, besides that, it is influenced by the thermal and energy performance of the refrigerator. Because of this, we established the proper mass of the refrigerant in a domestic refrigerator based on its minimum energy consumption; without neglecting the cooling capacity of the refrigerator. The methodology recommended by this specific refrigerator manufacturer defined the percent of operating time, energy consumption, average fresh food temperature and average freezer temperature. With this methodology, the thermal behavior of the refrigerator compartments is linked to the position of the damper, which controls the air flow and therefore also the temperature. Depending on the graduation of the damper, several positions can be defined (see Figure 2). For example, the position 9/9 indicates the set-point temperatures, FF=1.6°C, and FZ=-21.1°C. Therefore, the positions 9/9, 5/5 and 1/1 show a thermal profile in both compartments. In this work, tests configurations were 5/5 and 1/1.

First, the baseline was evaluated (a refrigerator with 100 g of R134a). Later, the charge process for the 3 refrigerators with R1234yf was started. Initial charge of R1234yf was set up at 70 g (30% below the baseline) and it was continually fed with increments of 7 g. Table 2 shows the refrigerant charge, which was evaluated for each refrigerator. Mass increments were performed through a bullet (a small volumetric capacity cylinder) previously charged with R1234yf; the measurements were done with a digital balance (± 0.01 g). The climatic chamber, from which the refrigerators were evaluated was set up at a temperature of 32.2°C ± 0.6°C and a relative humidity of 65% (according to the methodology used in this work). The test time depended on the speed, with which the thermal stability was achieved in the refrigerator compartments. Such criteria were related with temperature variations, whereas the thermocouple did not register variations above 0.6°C in three consecutive compressor cycles. For each test, the thermal conditions of the compartments, the heat exchangers (condenser and evaporator), and the energy consumption were measured to define the optimal charge of R1234yf and to compare the performance with R134a.

2.2 Instrumentation and measurements

The refrigerator, which was used for the analysis, has been completely instrumented in order to evaluate its thermal behavior and to provide experimental evidence. For temperature measurement in the compartments FF and FZ, and the components (compressor, condenser and evaporator), type T thermocouples (±0.03°C) were used. For the FF, 8 thermocouples were used and located inside containers of 0.470 l with a compound mixture of 80% and 20% of water and glycol, respectively. For temperature measurement in the FZ, 6 thermocouples were used and located inside wooden cubes of $5x10^{-2}$ m long. The blocks in the freezer were made out of wood, due its high humidity absorption of the surroundings, allowing steady temperature reading. Such kind of instrumentations were in line with the methodology recommended by the specific refrigerator manufacturer. Figure 3 shows the distribution of the thermocouples in one of the refrigerators used for the tests. During the tests, refrigerator doors were kept closed, ensuring them with thermal paste to avoid minimum gaps that could be made from the passage of thermocouples through the doors.

The main components were also instrumented with thermocouples at key points to assess the performance of R1234yf within them. In the evaporator, 5 thermocouples were placed along its length; in the condenser, 3 thermocouples were placed, and finally, one was placed in the compressor suction and another in the discharge line. These thermocouples were attached to the pipe wall with dielectric adhesive tape and thermal paste. Figure 4 illustrates the location of the thermocouples in both heat exchangers. For the condenser, temperatures were measured at the inlet, at the middle, and at the outlet of its length. For the evaporator, temperatures were measured at the inlet, at 1/2, at 3/4, at 7/8, and at the outlet, as seen in the figure. Suction and discharge pressure were measured using pressure transducers with a maximum uncertainty of a ±0.04 bar. Additionally, measurements for the energy consumption of the compressor and for the defrost system were taken by means of a digital wattmeter (± 0.4 W). The signals generated by the measurement devices were stored in a data acquisition system based on a PC using LabView software. The acquisition was done at intervals of 30 s during the test.

The evaluation of R1234yf in this study is mainly focused on the replacement easiness of the refrigerant in the refrigerator, and no changes were made to the design. In addition, the R1234yf features allow compatibility with the POE10 lubricant, which is included with the test refrigerator.

Once the optimum refrigerant charge is found, using the above methodology, we confirmed the energy consumption of the refrigerator with this charge, following the descriptive guidelines of the Mexican Norm NOM-015-ENER-2012 (Secretaría de Energía, 2012). Regulation establishes the maximum limits of energy consumption for domestic refrigerators that work with hermetic compressors.

3. Results and discussions

Figure 5 shows the thermal behavior registered by one of the thermocouples located at the center of the evaporator (blue line), as well as the energy consumption of the compressor (red line) in a 22 h lapse for one of the test refrigerators. After 17 h of testing, an increase on the temperature was appreciated due to the adaptive defrost system switching-ON, which almost reached 20°C. At the same time the energy consumption presented an increase of approximately 145% with respect to the normal consumption of the compressor, due to the electric resistance switching-ON. The defrost system was activated during a period of 0.25 h (a typical value with doors closed), and the defrost time interval was close to a total of 17 hours (8 hours ON-compressor).

The number of cycles considered for the thermal analysis and the charge estimation under the proposed methodology was the one, which represents a condition of stability. In general, in case that during the test time a defrost cycle is presented, the most stable cycles are those immediately before (see Figure 5), in this case, the three consecutive cycles. Thus, this stationary state is considered as the condition under which the corresponding analysis was performed for this paper.

3.1 Thermal behavior of the heat exchangers

Thermal behavior of R1234yf on the heat exchangers was a result of the average temperatures, which were related to the measurements of the three consecutive cycles, only when the compressor was working (ON). For the three test refrigerators, thermal behavior of the heat exchangers was analyzed based on the charge of the refrigerant R1234yf. Figures 6 and 7 only show the behavior of one of the test refrigerators with the aim of presenting the thermal aspects of R1234yf for different refrigerant charges. It is worth to mention that the 3 refrigerators showed very similar behaviors.

Figure 6 shows the thermal behavior of the refrigerant inside the condenser for the three locations of the thermocouples previously discussed and for the position 5/5 of the damper. It was observed that temperatures for the different charges of R1234yf presented maximum variations within the range of ±2°C with respect to the temperatures obtained with the refrigerant R134a (baseline). Because it is a very small variation, it is not easy to appreciate the effect of the mass charge.

Regarding the evaporator, Figure 7 shows the thermal behavior of the refrigerant along the heat exchanger, showing greater variations with respect to the condenser. Starting from 84 g of R1234yf, a phase change in the refrigerant can be induced (a line segment almost constant between positions 0 and 3/4). Another relevant point was at the position 3/4, on which the refrigerant presented an increase in its temperature (position 7/8) and subsequently a small decrease. This is because of the geometrical arrangement of the evaporator and the air circulation due to the position of the fan.

The superheating in this methodology is defined as the difference between the temperature in the middle position and the temperature at the outlet of the evaporator. Regarding the baseline, the superheating degree is of 0.15°C, although none of the refrigerant R1234yf charges achieved a superheating degree that low, the values that more closely approached were 0.85°C and 0.50°C, which correspond to the 112 g and 119 g of refrigerant, respectively. Taking in account that the R1234yf has lower latent heat capacity, it represents a greater amount of refrigerant.

3.2 The effect of the refrigerant charge

Figure 8 shows the effect of the refrigerant charge R1234yf on some typical vapor compression parameters. As the charge increases, more refrigerant was accumulated at the heat exchangers, and, therefore, the work pressure went up within the cycle; this can be seen in the Figure 8a and 8b. Furthermore, this increase caused a reduction of the superheating degree as shown in Figure 8c. With a large amount of refrigerant charges, the evaporator overflowed and formed a cold line suction to the compressor entrance, as shown in Figure 8d. These effects are similar to the ones reported by (Boeng and Melo, 2014; Björk and Palm, 2006).

Figure 9a presents an increase in the cooling capacity as the refrigerant charge increased, because the evaporator was filled with more refrigerant. But with small refrigerant charges, low cooling capacity was observed, resulting in a decrease in the evaporation temperature, as seen in Figure 9b. The explanation for this reduction was the starvation of the evaporator, which increased the superheating (see Figure 8c) (Primal et al. 2004). Finally, the charge increase also raised the condensation temperature, as shown in Figure 9c.

3.3 Thermal behavior of the compartments

Figure 10 shows the thermal results of the compartments for the three test refrigerators for different charges of R1234yf and the baseline R134a. These results were based on a room temperature of 32.2°C. The temperatures reported for the compartments FF and FZ correspond to the average of the temperatures registered in the 3 complete cycles (ON and OFF) before defrosting. Such behaviors correspond to the position of the damper 5/5 (FF=2.8°C y FZ=-17.8°C).

Figure 10a presents temperatures of the FF for the 8 charges performed with R1234yf and also for the baseline (100 g of R134a). A natural thermal variability is observed among the three refrigerators, whose working temperatures oscillated between 2.63°C (2.8-0.17°C) and 3.34°C (2.8+0.54°C), that is a temperature of only 0.54°C was achieved, which is higher than the one set at position 5/5. The temperatures of the FF with R134a oscillated between 3.13°C and 3.62°C. This was compared with the average temperature obtained in each charge of the 3 refrigerators; there was a maximum difference of 0.4°C with respect to the behavior using R134a.

The thermal behavior of the FZ is represented in Figure 10b. The thermal average of the refrigerators for the charge of 100 g (R134a) is -18.26°C, whereas the minimum average for R1234yf corresponds to a charge of 98 g (-19.49°C) and the maximum average temperature is a charge of 70 g (-17.44°C). For practical purposes, these variations in the FZ represented adequate compartments.

Based on the results, it can be said that the refrigerators using R1234yf achieved adequate temperatures for both compartments, regardless of the charge value of the refrigerant, this concludes that R1234yf achieves an adequate thermal capacity. With these results, a charge range for R1234yf closer to the thermal behavior of R134a could be established. However, the evaluation of the energy consumption will be the determinant factor to establish the aforementioned optimal refrigerant charge. Moreover, the effect of refrigerant charge is more evident at the heat exchangers.

3.4 Analysis of the energy consumption and optimal charge

The optimal charge estimation of R1234yf must be related to the energy consumption. In this paper, for the evaluation of the energy consumption the ON-time ratio is estimated first for each of the three stationary cycles, as follows:

$$\%ON = \frac{t_{ON}}{t_{total}} \quad \text{Eq. (1)}$$

Where t_{ON} represents the time of the compressor ON, and t_{total}, the time in the ON mode plus the time in the OFF mode, t_{OFF}. The number of cycles per day is determined with the following expression:

$$N_{cycles} = \frac{1440}{t_{total}} \quad \text{Eq. (2)}$$

The factor 1440 corresponds to the minutes within a day. In order to find the energy consumption, *EC*, the following equation is used:

$$EC = \frac{\Delta E}{t_{cycle}}\left(\frac{8760}{1000}\right) \ [kWh\ yr^{-1}] \quad \text{Eq. (3)}$$

ΔE [Wh] corresponds to the difference between the measurement of energy in the first cycle and the last energy value reported in the third cycle. The time, t_{cycle} [h], represents the addition of the total time in each of the three cycles, and the conversion factor 8760/1000 allows to have the units of [kWh yr^{-1}]. Therefore, the latter equation shows the energy consumption for both damper positions (1/1, 5/5). The energy consumption for both positions was essential to establish the consumption for the optimum charge of the R1234yf.

Table 3 shows the energy parameters obtained for the refrigerant R134a as well as those for the different charges of R1234yf, the latter was under a climatic room temperature of 32.2°C. Hence, the table shows information about the time of the ON and OFF modes of the compressor, which correspond to the average time of the three stationary cycles (before the defrost period). Moreover, the percentage of the ON mode in the compressor and the number of cycles of the compressor during one day are reported. Finally, an interpolated energy consumption is shown, EC_{int}, which corresponds to the value that would be obtained from the exact temperatures of the FF=7.2°C and the FZ=-14.4°C (position 1/1, see Figure 2) based on the Mexican norm (Secretaría de Energía, 2012). To establish the aforesaid value, it was necessary to perform an interpolation among the obtained values from the energy consumption and those values reached in the FF and FZ for the positions 1/1 and 5/5. The following equations show the procedure to find the EC_{int}, which corresponds to the maximum value among both.

$$EC_{7.2°C} = EC_{1/1} + \frac{(EC_{5/5} - EC_{1/1})(7.2°C - T_{FF,1/1})}{T_{FF,5/5} - T_{FF,1/1}} \qquad \text{Eq. (4)}$$

$$EC_{-14.4°C} = EC_{1/1} + \frac{(EC_{5/5} - EC_{1/1})(-14.4°C - T_{FZ,1/1})}{T_{FZ,5/5} - T_{FZ,1/1}} \qquad \text{Eq. (5)}$$

For the refrigerant R1234yf a unique test in the position 1/1 for the charge of 70 g was performed. This was the charge used to perform the interpolation with the other charges.

The value obtained was far enough from the point of interest (position 5/5) and the error that is introduced is minimal and allowed to reduce the evaluation time. Therefore, interpolation provided the values of the energy consumption, one for the FF and the other for the FZ; the table shows the maximum among both.

To determine the optimal charge, an energy consumption analysis *versus* refrigerant charge analysis was performed, as shown in Figure 11. The points represent the data experimentally obtained in the three test refrigerators (see Table 3). The average uncertainty for the energy consumptions was ±1.095 [kWh yr^{-1}] for the interpolated energy consumption. An optimal consumption (minimum between units) can be identified visually through a quadratic regression. The curves represented by lines correspond to the quadratic regressions of the experimental curves and they are the ones to be considered to determine the optimal charge. It is worth to mention, that the same optimal charge value was not obtained for the refrigerators; this is normal, because it shows the natural variations between units. Therefore, the optimal point in each curve represents the charge of R1234yf with the least energy consumption. For each regression, an optimal charge was obtained, from which it is established that the value to be considered is the average of the three of them. Therefore, the obtained value was 92.2 g that correspond to a 7.8% lower than the charge with R134a (100 g).

The average of the experimental evaluation of the energy consumption for this optimal charge of R1234yf subject to the criteria of the Mexican Norm NOM-015-ENER-2012 (Secretaría de Energía, 2012) corresponded to 375.95 kWh yr^{-1}, which represented an increase of 4% with respect to the baseline of R134a (361.35 kWh yr^{-1}) for the same operating conditions.

Based on the previous results, the refrigerator, which worked with R1234yf presented a very similar behavior to that which worked with R134a, with a small energy consumption increase. It should be remembered that these results were obtained without performing any modification to the refrigerator.

4. TEWI analysis

The concept of total equivalent warming impact, TEWI, was developed as a measure of the combined global warming impacts of the refrigerant losses to the atmosphere and the CO_2 emissions from fossil fuels to generate power to run the refrigerating equipment (Fisher, 1993). Therefore, a TEWI analysis was performed to assess the saved CO_2 equivalent emission replacing R134a with R1234yf in domestic refrigeration systems. The TEWI analysis takes into account both, direct (due to refrigerant leakages) and indirect (compressor electricity consumption) emissions. Equation (6) represents the total equivalent warming impact (European Committee for Standardization/Technical Committee, 2008):

$$TEWI = GWP \cdot L \cdot n + \left(GWP \cdot m \cdot (1-\alpha)\right) + n \cdot EC \cdot \beta \qquad \text{Eq. (6)}$$

In this equation, L is the average annual refrigerant leakage; n, is the system life time; m the mass charge of refrigerant; α, the percentage of refrigerant recovered and the end of the life time of the system; EC, is the energy consumption; and β is the CO_2 emission factor.

The first and the second summands of the equation (6) correspond to the direct emissions and the third one to the indirect emissions. The required values for the TEWI calculation have been extracted from the IIR Guideline (International Institute of Refrigeration, 2016), and β was based on GEI Program Mexico (ProgramGEI, 2013). The results of the TEWI evaluation for R134a and R1234yf are shown in Table 4. It is worth to mention, the extent of the CO_2 factor emission, which considerably affects the indirect emissions, which could be significantly reduced if Mexico would have a greater reliance on renewable energies.

Even though direct emissions were almost negligible for R1234yfm due to its GWP value close the unity; the resulting TEWI for this alternative was 1.07% higher than R134a and there were no environmental benefits compared to the utilization of the low GWP alternative in an R134a domestic refrigerator without modifications. A combination of a capillary tube and the refrigerant charge, as well as the resizing of pipelines may reduce the energy consumption, which showed better performance than those of R1234yf. On the other hand, the topic to address has to do with safety normative, which at this moment is limited to domestic refrigeration.

5. Conclusions

In this paper, an experimental study using R1234yf as a drop-in replacement for R134a in domestic refrigerators has been presented. The optimal charge of R1234yf has been determined proposing an alternative methodology based on the minimum energy consumption. 3 completely instrumented refrigerators were used for the evaluation of R1234yf, thus obtaining higher reliability in the results. The main conclusions of this paper are summarized as follows:

- The thermal behavior of the refrigerator compartments FF and FZ, and in the heat exchangers was analyzed. The average temperatures of the compartments FF and FZ in the different R1234yf charges were relatively close to those of R134a, concluding that R1234yf presents thermal loads very similar to those shown by R134a. The design of the refrigerators was not modified in any way.
- The three refrigerators were evaluated varying from 70 g with increments of 7 g up to 119 g of R1234yf, including those with R134a (baseline). These tests were performed for the damper positions 1/1 and 5/5.
- The thermal behavior of the alternate refrigerant was analyzed in the condenser and the evaporator, resulting in a major thermal variation in the evaporator due to the refrigerant charge.
- At the same time, during the tests, the energy consumption was measured and with this the consideration of an optimal charge regarding a minimum energy consumption was reduced. Quadratic regressions were performed to estimate the

R1234yf charge resulting in 92.2 g. Based on this result, there was an increase of 4% in the energy consumption when using R1234yf with respect to R134a.

- Finally, a TEWI analysis was performed, showing that R1234yf is 1.07% higher than R134a, where the possible energy improvements could focus on the size of the capillary tube, pipelines or the compressor. Thus, the R1234yf would be more attractive for use in domestic refrigeration.

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Figure 1. Experimental refrigerator.

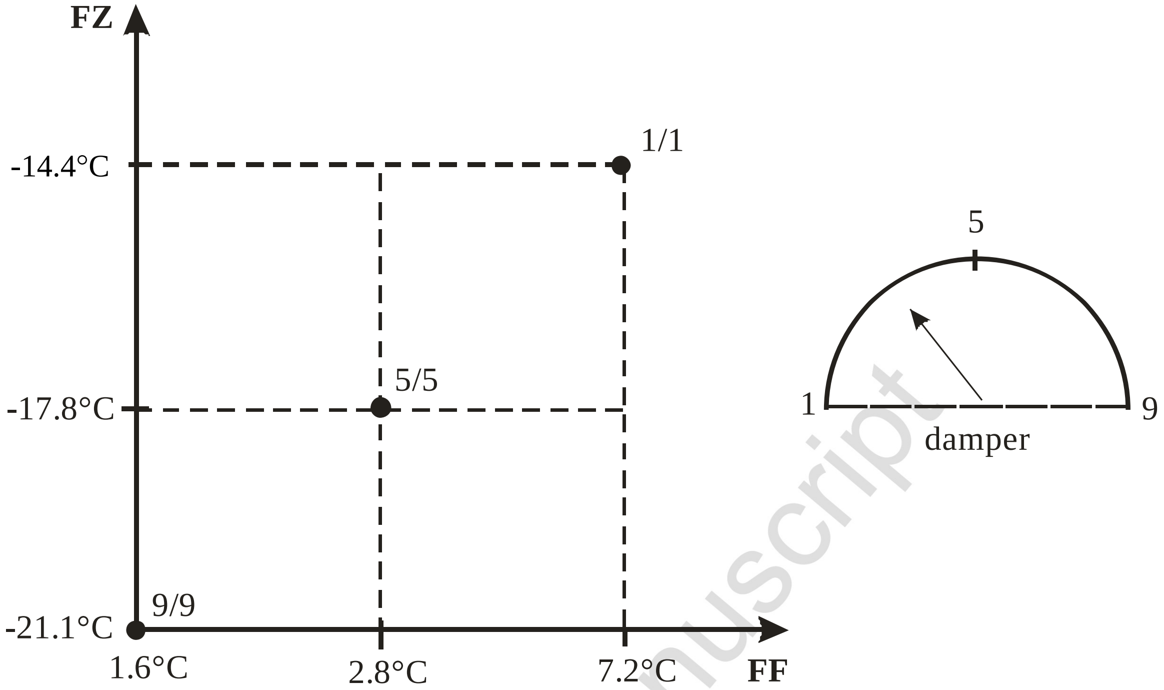


Figure 2. Temperature configuration depending on the position of the damper.

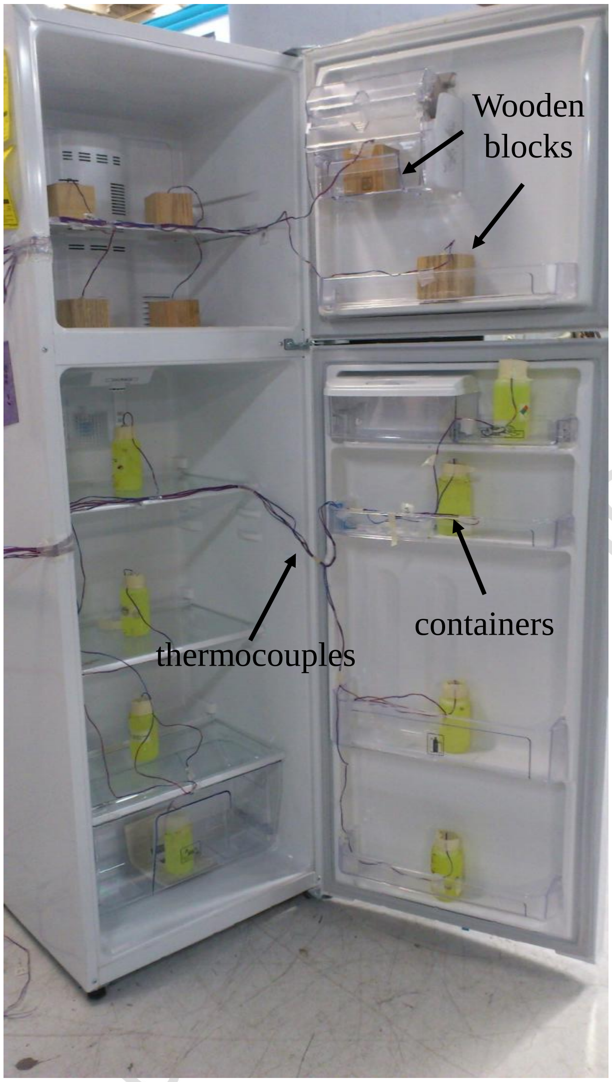
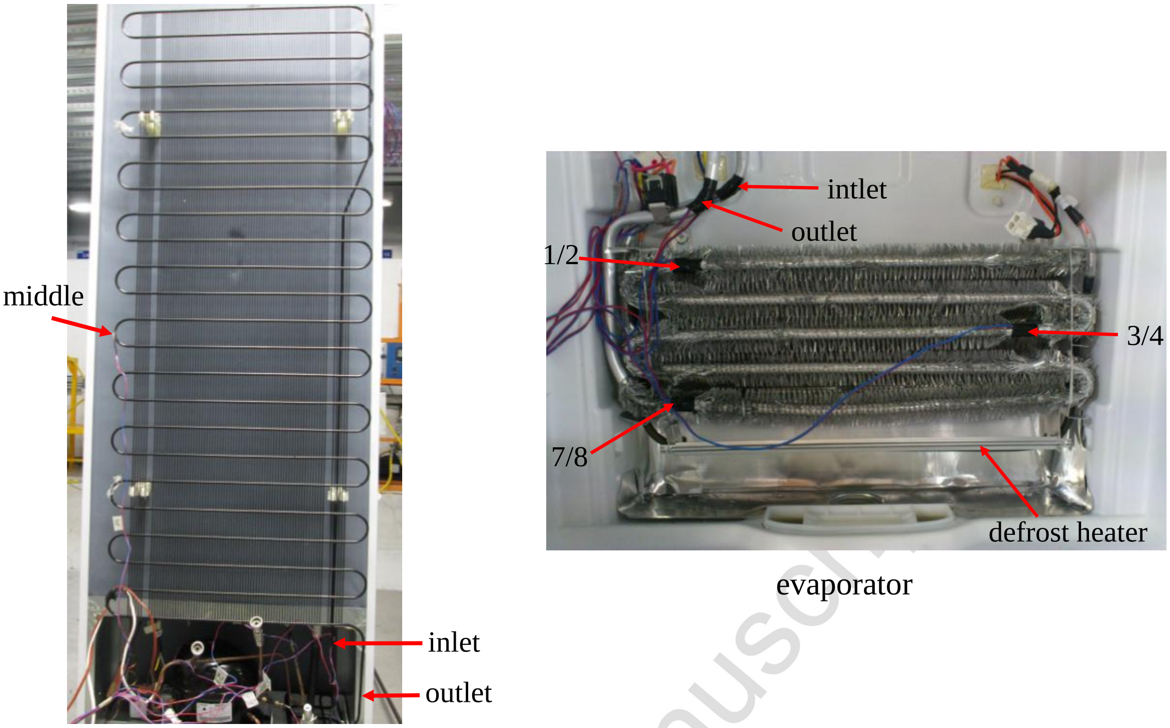


Figure 3. Location of the thermocouples in the refrigerator compartments.



evaporator

condenser

Figure 4. Location of the thermocouples at the heat exchangers.

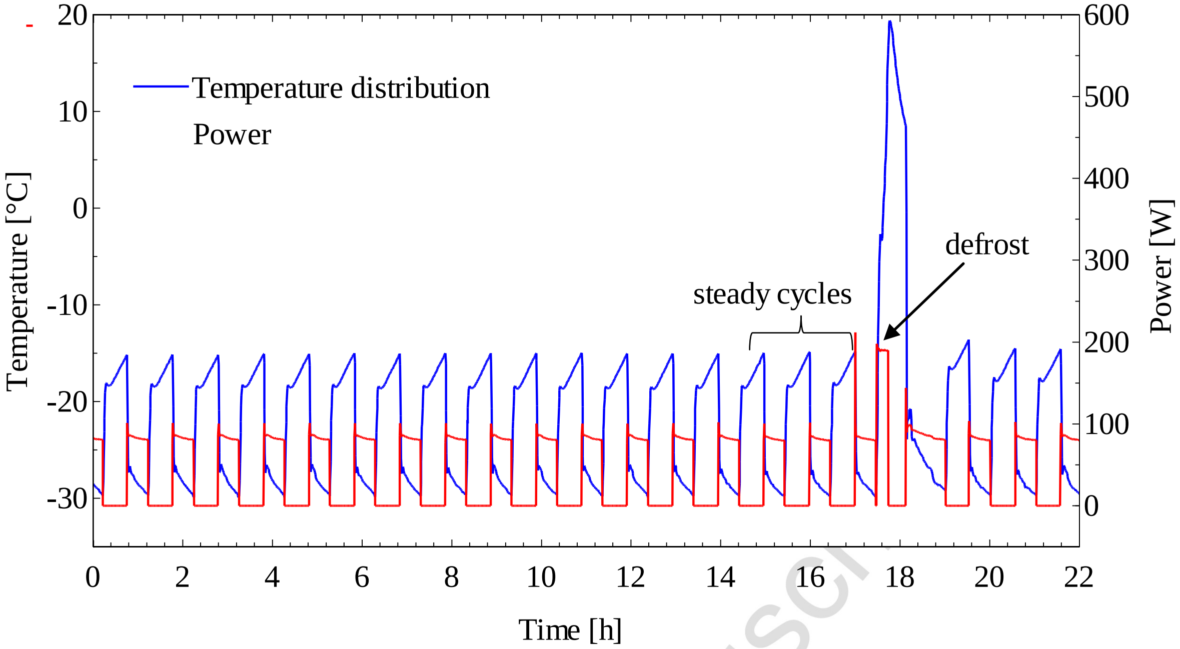


Figure 5. Defrost period and stationary cycles.

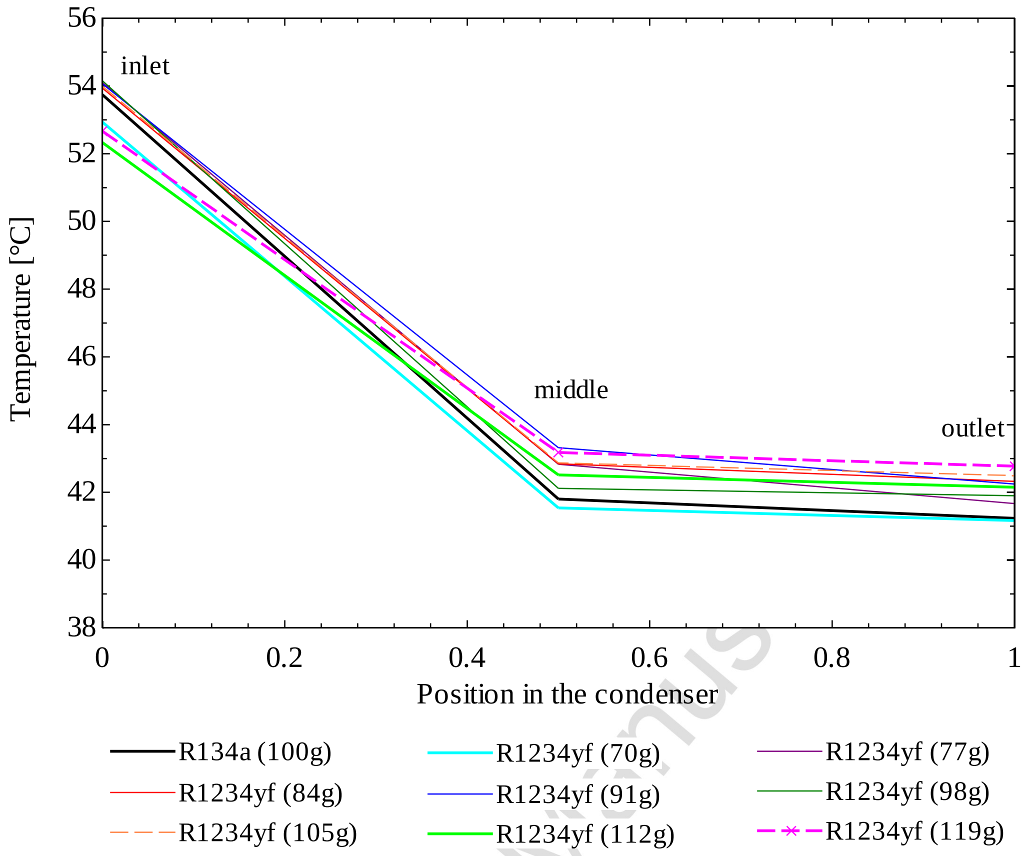


Figure 6. Thermal behavior along the condenser.

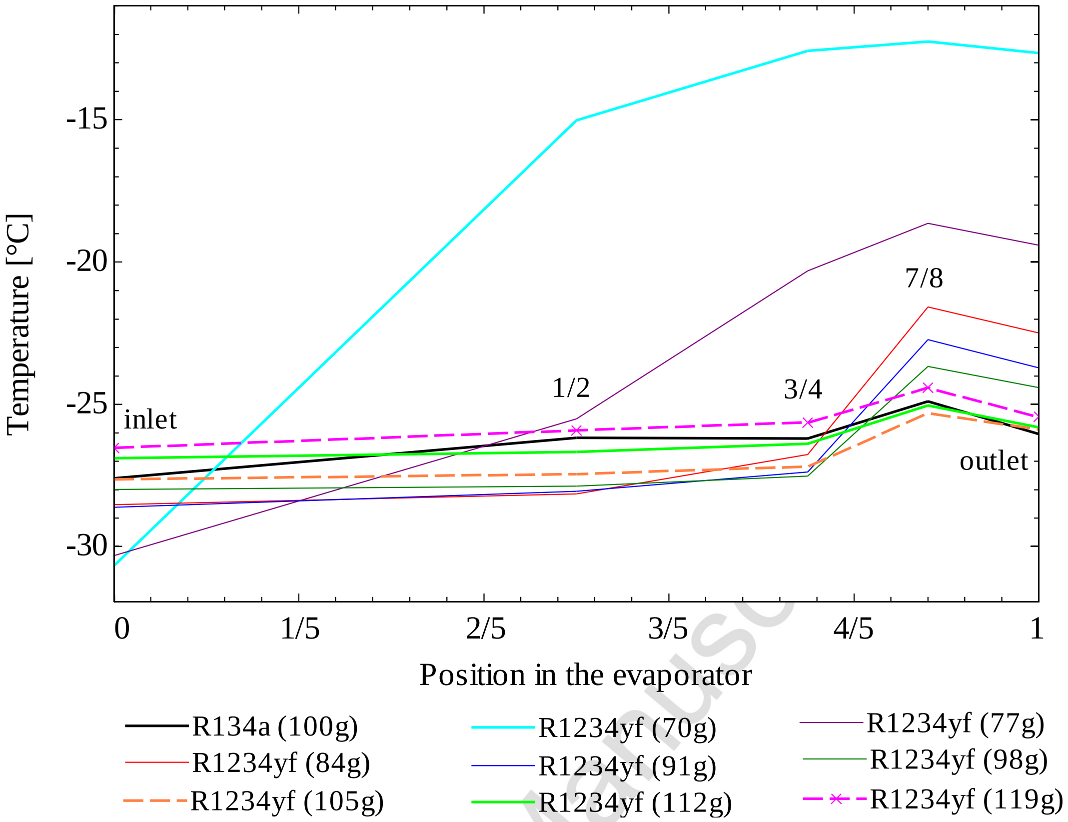
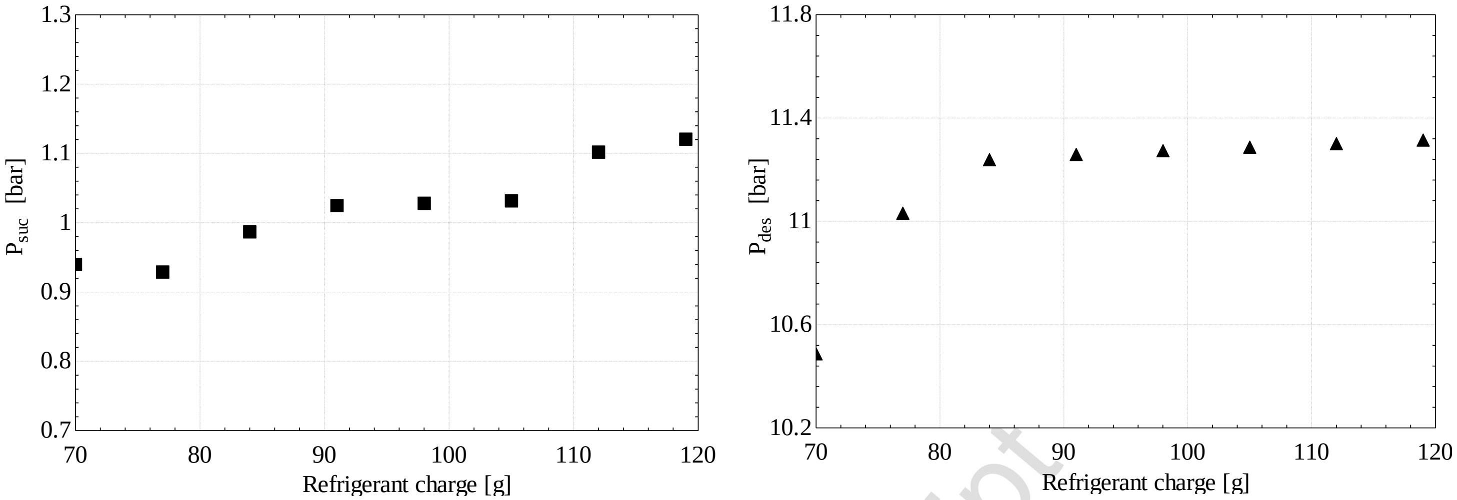
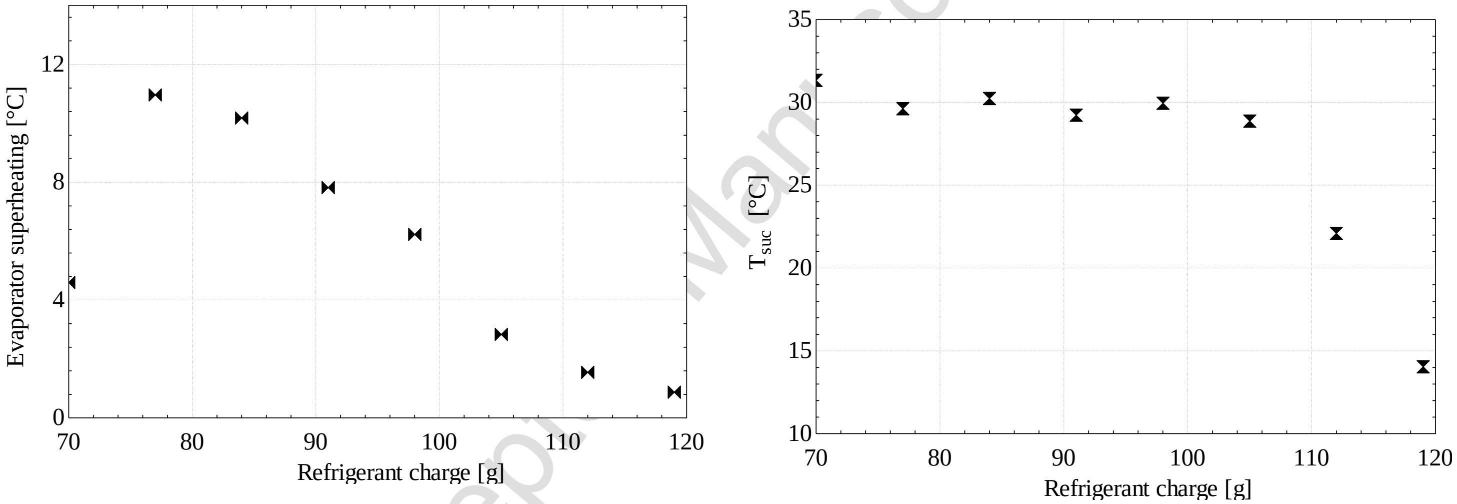


Figure 7. Thermal behavior along the evaporator.



a) Evaporating pressure

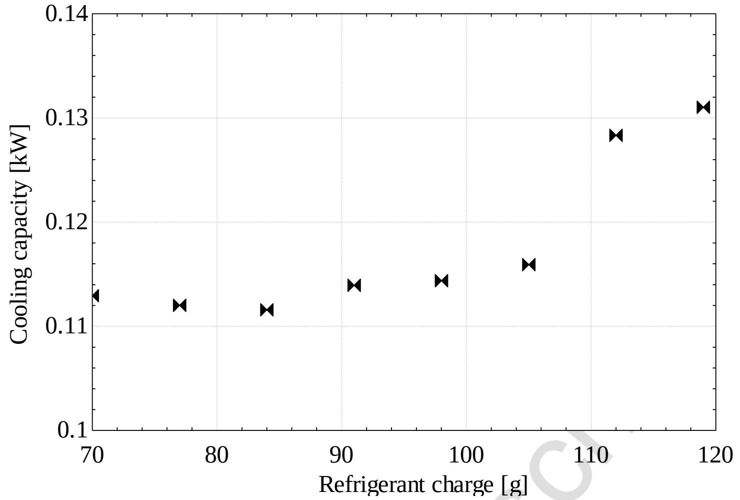
b) Condensing pressure



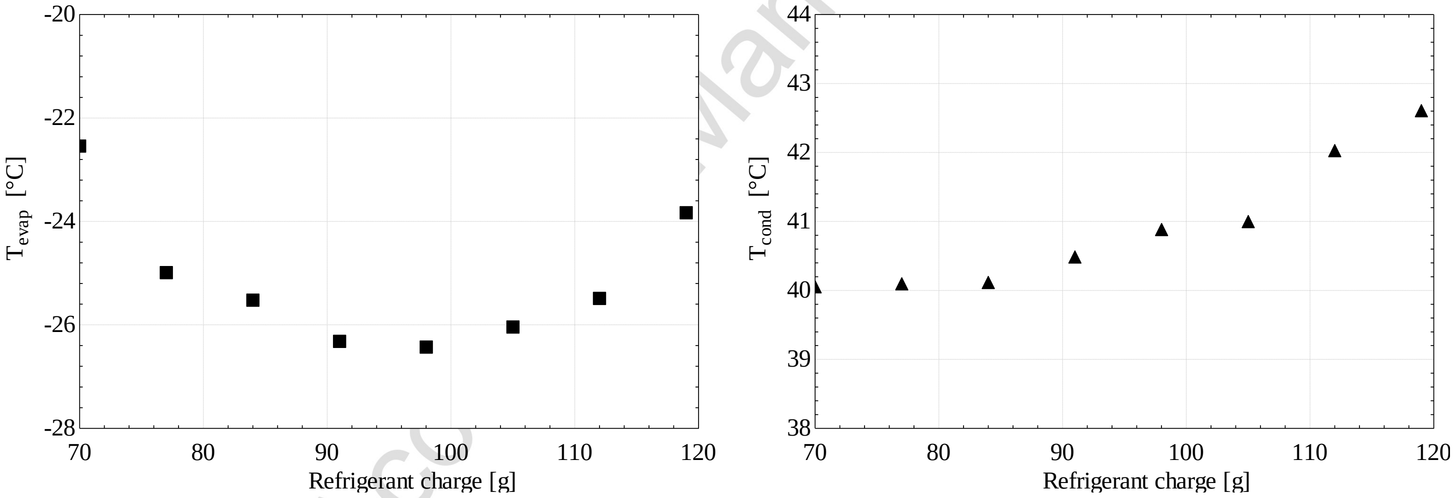
c) Superheating

d) Suction temperature

Figure 8. Evaporating and condensing pressure, superheating and suction temperature vs. refrigerant charge.



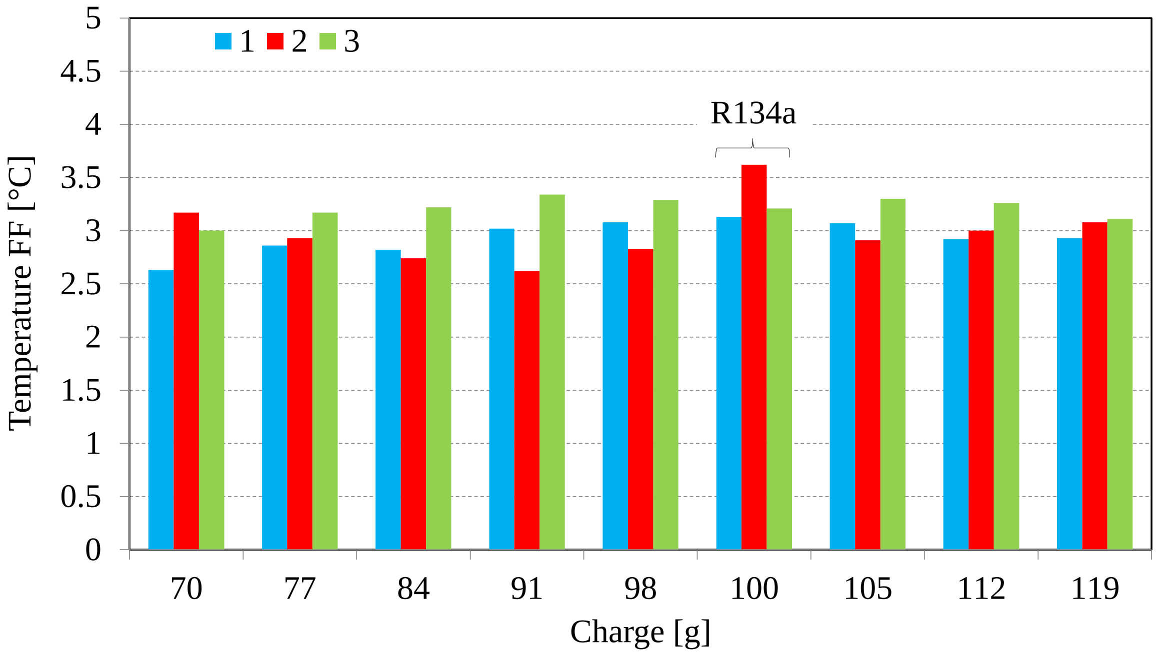
a) Cooling capacity



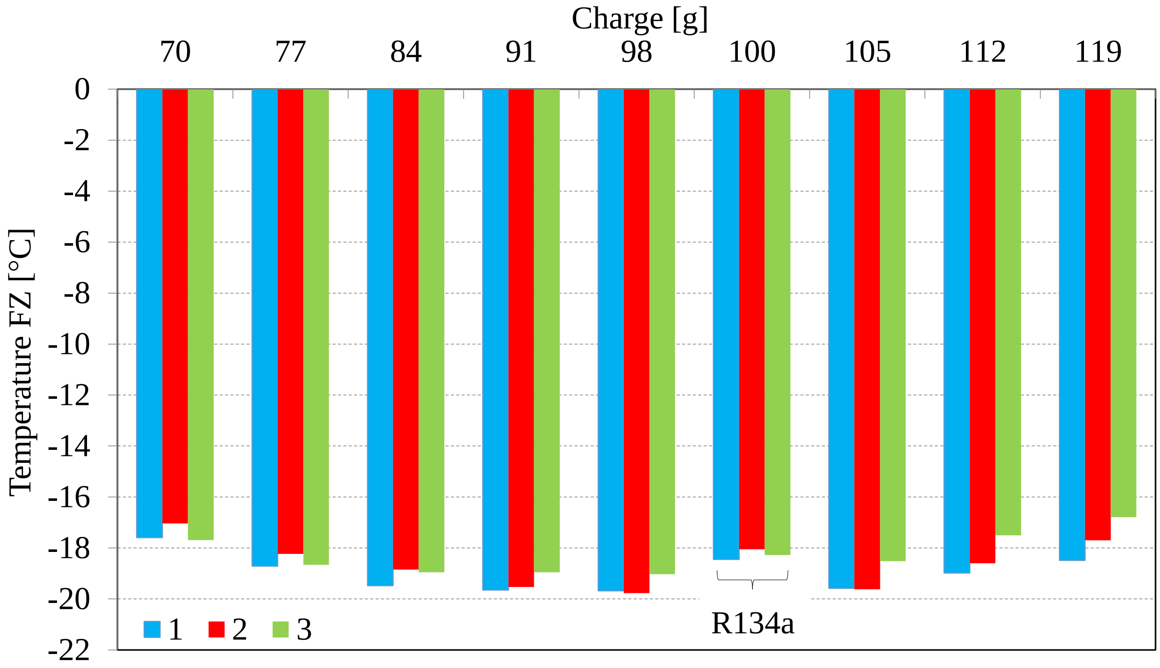
b) Evaporator temperature

c) Condenser temperature

Figure 9. Cooling capacity, evaporator and condenser temperature vs. refrigerant charge.



a) fresh food compartment



b) freezer

Figure 10. Thermal behavior of the compartments in the three refrigerators.

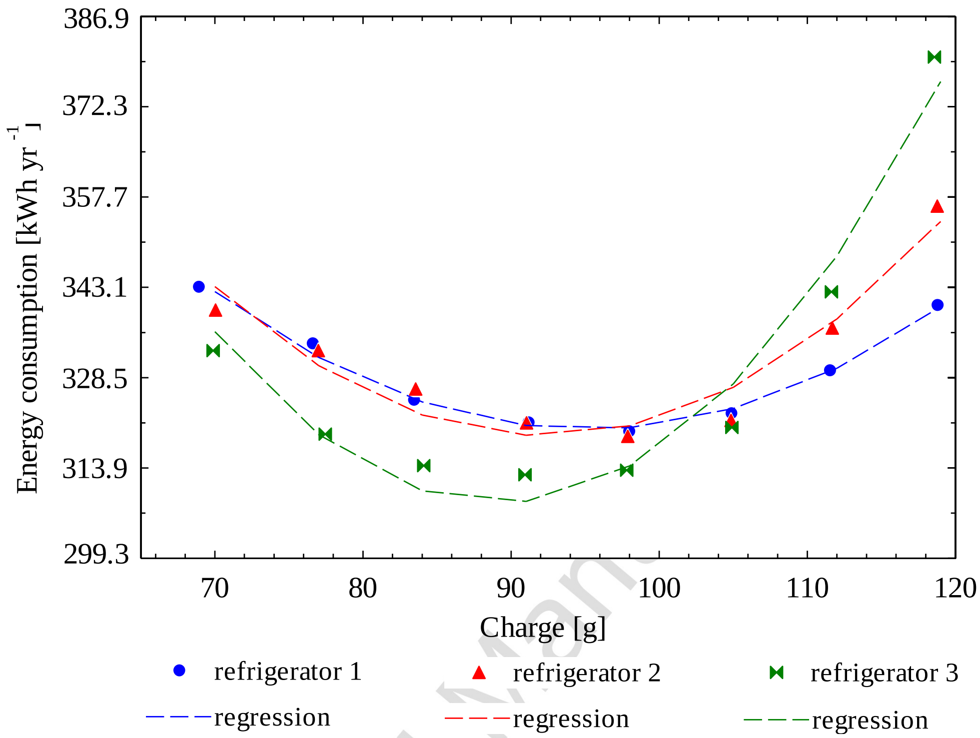


Figure 11. Energy consumption *versus* refrigerant R1234yf charge.

Table 1. Main technical characteristics of the experimental refrigerator.

Component	Characteristics	Component	Characteristics
Compressor	Hermetic reciprocating 115-127 V Frequency 60 Hz Capacity of 0.175 kW	Condenser	Static of 24 tubes Internal diameter of the tube = 4.57×10^{-3} m Wire diameter = 1×10^{-3} m Natural convection
Capillary tube	Internal diameter = 6.6×10^{-4} m Length = 2.43 m	Evaporator	Aluminum material, finned and inner grooved External diameter of the tube = 9.5×10^{-3} m Automatic defrost Forced convection

Table 2. Refrigerant charge.

Refrigerant	Charge [g]
R134a	100
R1234yf	70
	77
	84
	91
	98
	105
	112
	119

Table 3. Energy parameters of the test refrigerators.

Refrigerator 1											
	R134a		R1234yf								
charge	100		70		77	84	91	98	105	112	119
position	1/1	5/5	1/1	5/5	5/5	5/5	5/5	5/5	5/5	5/5	5/5
t_{ON}	23.85	30.52	35.88	39.91	34.88	29.67	28.49	27.72	28.21	29.52	30.53
t_{OFF}	44.63	32.02	42.59	31.02	32.19	32.19	32.53	32.71	32.89	33.38	33.04
%ON	35	49	46	56	52	48	47	46	46	47	48
N_{cycles}	21.03	23.03	18.35	20.30	21.47	23.28	23.60	23.83	23.57	22.89	22.65
EC_{int}	**286.2**		**343.1**		**333.9**	**324.8**	**321.2**	**319.7**	**322.6**	**329.6**	**340.2**
Refrigerator 2											
t_{ON}	20.79	25.64	29.18	31.86	20.61	19.29	17.95	17.10	17.11	18.61	19.78
t_{OFF}	40.74	29.17	38.22	28.48	19.62	19.45	20.13	20.11	20.12	20.12	19.79
%ON	34	47	43	53	51	50	47	46	46	48	50
N_{cycles}	23.40	26.67	21.36	23.86	35.79	37.17	37.81	38.70	38.68	37.18	36.39
EC_{int}	**287.6**		**339.4**		**332.9**	**326.7**	**321.2**	**319**	**321.6**	**336.5**	**356.2**
Refrigerator 3											
t_{ON}	24.15	30.54	31.03	35.67	31.02	28.68	26.33	27.64	28.49	29.72	33.19
t_{OFF}	43.30	30.67	40.74	30.68	29.52	30.67	31.22	31.17	31.18	30.70	29.69
%ON	36	50	43	54	51	48	46	47	48	49	53
N_{cycles}	21.35	23.53	20.06	21.70	23.79	24.26	25.02	24.48	24.13	23.83	22.90
EC_{int}	**299.7**		**332.9**		**319.4**	**297.8**	**312.8**	**313.5**	**320.5**	**342.4**	**380.3**

Table 4. Results for TEWI.

Parameter	R134a	R1234yf
GWP	1300	1
L [kg per year]	0.002	0.001844
n [years]	15	15
m [kg]	0.1	0.0922
α [%]	70%	70%
EC [kWh per year]	361.35	375.95
β [kg CO_2-eq kWh^{-1}]	0.49	0.49
Direct emissions [CO_2-eq]	78	0.055
Indirect emissions [CO_2-eq]	2655.922	2763.232
TEWI [CO_2-eq]	2733.922	2763.287