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HFO-1234ze Analysis as an Ecological Alternative In Domestic Refrigeration

Análisis del HFO-1234ze como alternativa ecológica en la refrigeración doméstica

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Abstract

Food refrigeration is an essential process in homes, and thus a home refrigerator becomes an indispensable appliance. Being this one of the biggest consumers of electrical energy and contamination due to the refrigerant used for its operation, it is important to look for alternatives that improve this process. This study aims to implement the HFO, R12354ze as an ecological alternative in domestic refrigeration, in response to environmental demands to reduce climate change and deterioration of the ozone layer. Through a thermodynamic and heat transfer analysis, simulating the cooling cycle and the behavior of the fluid in heat exchange using specialized software and CFD, the HFO is presented as an acceptable alternative achieving cooling parameters which are between 5% and 8% different from common refrigerators currently used, with an environmental cost up to 99% lower, without altering their energy efficiency. Taking advantage of the properties of the HFO, it is possible to improve the coefficient of performance of the cooling cycle by 12%.

Keywords: CFD, HFO, Kigal amendment, Paris agreement, refrigeration, R1234ze.

Resumen

La refrigeración de alimentos es un proceso esencial en los hogares, por lo que un refrigerador doméstico se convierte en un electrodoméstico indispensable. Siendo este uno de los mayores consumidores de energía eléctrica y de contaminación por el refrigerante que ocupa para su funcionamiento, es importante buscar alternativas que mejoren este proceso. En este estudio se pretende implementar un HFO, el R12354ze, como alternativa ecológica en la refrigeración doméstica, en respuesta a las demandas ambientales para reducir el cambio climático y el deterioro de la capa de ozono. Mediante un análisis termodinámico y de transferencia de calor con simulaciones del ciclo de refrigeración y el comportamiento del fluido en el intercambio de calor utilizando *software* especializado y CFD, se presenta al HFO como una alternativa aceptable logrando parámetros de refrigeración en rango entre 5 %-8 % de diferencia con refrigeradores comunes utilizados actualmente, con un costo ambiental de hasta un 99 % más bajo, sin alterar su eficiencia energética. Aprovechando las propiedades del HFO en el ciclo de refrigeración se logra mejorar el coeficiente de desempeño del ciclo de refrigeración en un 12 %.

Palabras clave: Acuerdo de París, CFD, HFO, enmienda Kigal, refrigeración, R1234ze

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1. Introduction

Historically, the mechanical refrigeration that uses fluids for heat transfer has passed through various stages to adapt to environmental needs. Starting with the Vienna Convention for protecting the ozone layer (1985), which forced to reach the Montreal Protocol (1995) regarding substances that deteriorate such layer (mainly CFC and halogens); this agreement was successful and the proposed goals were accomplished. In 2003 it was seen as the most successful protocol until then; it was frozen in 2015, and it is expected to completely eliminate the HCFCs by 2030 in the developed countries, and by 2040 in the remaining countries [1].

As a consequence, the United Nations create other treaties and agreements for protecting the ozone layer and the environment, among which it is highlighted the Paris Agreement in 2015 that created the 2030 agenda, which requests to accelerate the reduction of worldwide emissions of greenhouse gases, seeking to maintain the global temperature increase far below 2 °C in this century [2]. In this context, in 2016, with the Kigali amendment to the Montreal Protocol, an agreement is reached to gradually eliminate the hydrofluorocarbons (HFC); even though they have a null or low Ozone Depletion Potential (ODP), they possess a high Global Warming Potential (GWP), which increases the planet temperature. This amendment took effect on January 1st, 2019, to reduce the production and consumption of HFC in more than 80% during the next thirty years [3].

With the meeting in Kigali it is agreed to reduce up to placating the use of refrigerants with high GWP, promoting the switching to alternatives less harmful to the enviroment and improving the energy efficiency in refrigeration and air conditioning. The opportunity to change is very accepted, and in many cases results profitable in industrial refrigeration and refrigerated transport, and to a lesser extent in commercial refrigeration; however, the change results more costly in the cases of mobile and commercial air conditioning and domestic refrigeration and, therefore, it is more difficult to move away from HFCs. In addition, in underdeveloped countries and countries with high environmental temperature the change results more costly and difficult compared to developed countries [4]. With the regulations and taxes to the refrigerants with high GWP, it is seeked to make more complicated for manufacturers to produce household appliances with these refrigerants, making industry and researchers to focus on looking for more ecological alternatives, which do not result in relatively high costs in the adaptation or replacement in refrigeration and air conditioning equipment which has been in use.

HFOs, also called hydrofluoroolefins, might be one of the main alternatives for the field of refrigeration; they are currently the fourth generation of refrigerants. In the International Fair of Green Energies in Refrigeration and Air Conditioning, the chemical engineer Nohora Clavijo explained that the HFOs are double bond organic compounds with a shorter atmospheric life, and consequently they have less environmental impact. In addition, the Honeywell company communicated that mixtures HFO/HFC will be utilized to reduce the use of hydrofluorocarbons.

In experimental analyses conducted to compare HFO with the HFC-134a in a vapor compression system, the difference in the coefficient of performance (COP) obtained for the R1234yf is between 3 and 11% smaller to the one obtained using R134a, and for R1234ze is only between 2 and 8% below, using the same compressor for the three cases [5]. In a research involving an energy analysis in a vapor compression system, Yataganbaba *et al.* [6] found R1234yf and R1234ze as appropriate replacements for R134a, with this being the refrigerant mostly used in domestic refrigeration. The HFOs may work similarly in domestic refrigeration systems, without having the environmental penalty of the HFC.

1.1. Low levels of GWP and high safety

The GWP, or global warming potential, of a chemical substance is a consequence of the combination of its radiative forcing or climatic forcing (change in the net irradiance in the transition zone between the troposphere and the stratosphere due to a change in the atmospheric concentration of a gas) and its useful atmospheric life (time it remains in the atmosphere without being disintegrated) [7].

Since hydrofluoroolefins are fluoridated compounds without carbon, they have low levels of GWP and a null ODP, fulfilling the regulations established to protect the ozone layer and the enviroment. In addition, HFOs, as opposed to hydrocarbons (HC), do not have a high risk of flammability, with ASHRAE safety classification between A1 and A2, low or null flammability.

Another great advantage of these refrigerants is their compatibility with a great variety of lubricant oils, and it is not necessary to make important adaptations in existing systems that operate with HFC or HCFC. It does not cause wear in materials due to corrosion, and due to their properties, it does not cause high fatigue in the compressor.

1.2. Implementation of R1234ze in domestic refrigeration

Most vapor compression domestic refrigerators use HFC as working fluid in the cycle; these do not directly damage the ozone layer, but contribute to the greenhouse effect, with R134a being the mostly used. They are also being employed as ideal substitutes to hydrocarbons for domestic refrigeration, products such as R600a, which has a very low contribution to global warming; however, they are highly flammable if they are not used properly, and it is necessary to replace the complete installation. On the contrary, the HFO-1234ze needs ten times more concentration and 250,000 times more energy than hydrocarbons to become inflamed, only above 30 °C. It is catalogued as a low toxicity and slightly flammable fluid [8–10].

The refrigerant (HFO) R1234ze has efficiency characteristics very similar to the HFC R134a and operates at similar pressures, and so it is not necessary to make important changes to existing systems. The atmospheric life of the refrigerant as a residue is only eighteen days, much smaller than the thirteen years of the R134a. A unique characteristic of the R1234ze is the absence of flammability when mixed with air at less than 30 °C of ambient temperature. For this reason, it is considered not flammable for manipulation and storage [11], [12]. In the research work by Ngoc [13] about a refrigeration cycle that uses HFO-1234ze, HFO-1234yf, R22 and R32 as alternatives to R134a, results show that the cycle that uses R1234ze as refrigerant has the highest coefficient of performance.

Due to these compatibilities and characteristics, a refrigeration system of medium or low pressure|, in this case a domestic conventional refrigerator, may be coupled to operate with R1234ze without requiring important changes to the system.

2. Materials and methods

In the study, the refrigeration cycle that will operate with R1234ze was designed according to the data obtained from a functional domestic refrigerator that operates with R134a. The Genetron Properties software provided by Honeywell and the database of the Buffalo – NY-USA Research Lab are used to model this thermodynamic cycle. In addition, for analyzing the heat transfer of the refrigerant in the refrigeration cycle, a CFD study is conducted using Fluent from ANSYS, in which tests of evaporation in the corresponding device and of temperature distributions in the household appliance are carried out, simulating the real operating conditions.

2.1. Characteristics of the refrigerant

The HFO 1234ze is a pure fluid with low toxicity and flammability, constituted by fluor, hydrogen and oxygen molecules. Table 1 presents the properties of this fluid and compares them with refrigerant 134a.

Table 1. Properties of R134a and R1234ze

Property	R134a	R1234ze
Molecular weight (kg/kmol)	102	114
Critical temp. (°C)	101,1	109,4
Density (kg/m^3)	511,9	489,23
Critical pressure (kPa)	4059	3636
ODP	0	0
GWP	1300	1
ASHRAE classification	A1	A2L

Data taken from the Honeywell catalog [12] and REFPROP [14]

2.2. Refrigeration cycle

For studying the refrigeration cycle, cycle conditions in a refrigerator with R134a for subtropical climate, nominal power of 0.104 kW, and operating with a 1/5 HP Embraco EM3U50HLP compressor, are taken. Table 2 presents the properties of this reference refrigerator.

Table 2. Characteristics of the reference refrigerator

Characteristic	Value
Name	No-frost domestic refrigerator
Type of refrigerant	R134a
Mass of refrigerant	95 kg
Nominal power	104 W
Nominal volume	250 l
Freezer volumen	55 l
Refrigerator volumen	184 l

The refrigerator operates with evaporation and condensation temperatures of –23.3 °C and 54.4 °C, respectively, and the thermodynamic cycle for the R134a is developed according to these conditions. The parameters of the cycle are defined by means of the thermodynamic properties of the refrigerant at the operating conditions in the refrigerator. Figure 1 shows the P-h diagram of the refrigeration cycle with R134a which was made using EES [15] and the data obtained experimentally.

In the calculation of the fundamental performance parameters of the refrigeration cycle, the coefficient of performance (COP) is calculated using Equation 1, and this parameter represents the ratio between the cooling capacity and the energy cost caused by the compression cycle.

$$COP = \frac{Q_e}{W_c} \tag{1}$$

$$Q_e = (h_1 - h_4)\dot{m} \tag{2}$$

Where:

Q_e: Cooling capacity , [W]
W_c: Power consumed, [W]
h_1: Evaporator output enthalpy, [kJ/kg]
h_4: Evaporator input enthalpy, [kJ/kg]
$\dot{m}$: Mass flow of refrigerant, [kg/s]

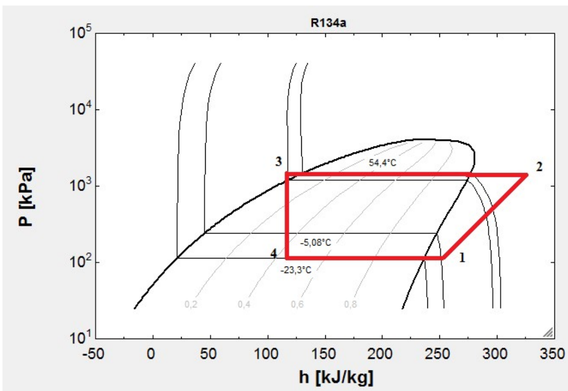


Figure 1. P-h diagram, real refrigeration cycle with R134a [15]

The isentropic efficiency of the compressor is the entropy generated in the real compression compared to the one generated ideally. This parameter is defined by Equation 3.

$$\eta = \frac{h_{2s} - h_1}{h_{2a} - h_1} \tag{3}$$

Where:

η: isentropic efficiency
h_{2s}: Cooling capacity, [kJ/kg]
h_{2a}: Power consumed, [kJ/kg]

2.3. Refrigeration cycle adapted to R1234ze

For comparing the performances of R1234ze and R134a, the cycle of the reference domestic refrigerator is theoretically adapted to operate with HFO, without altering the operating conditions. For this purpose the refrigeration cycle is designed, using Genetron Properties, maintaining the original parameters of the refrigerator under study and entering the power consumed, condensation temperature, evaporation temperature and compressor efficiency. This simulation will be called case A. Figure 2 and Figure 3 present the P-h and T-s diagrams, respectively, of the refrigeration cycle with R1234ze.

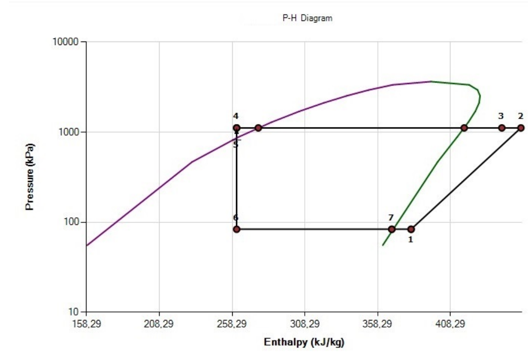


Figure 2. P-h diagram, real refrigeration cycle with R1234ze

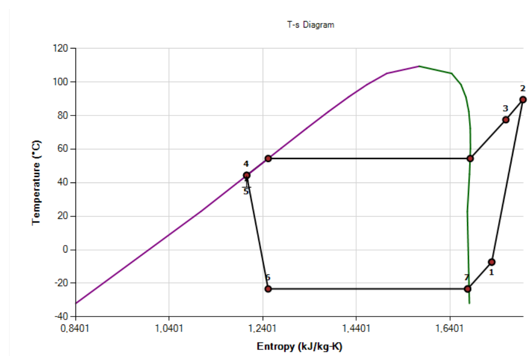


Figure 3. T-s diagram, real refrigeration cycle with R1234ze

2.3.1. Improvements to the thermodynamic cycle

According to the indications of the R1234ze suppliers, the COP of the cycle could be improved compensating the cooling capacity of the system with particular adjustments in it, and besides, improving the performance of the compressor would increase the efficiency of the refrigerator with HFO. The quality of the mixture at the outlet of the evaporator may be better with R1234ze than with R134a, if the heat flow is sufficiently low or if the mass velocity is sufficiently high [16] besides, it has been experimentally seen that the COP improves for cycles with R1234ze at greater values of evaporation temperature [5]. On the other hand, Sánchez *et al.* [17] indicate that a compressor with larger displacement should be used, to achieve the same cooling capacity than with a system with R134a.

An improved cycle is proposed, where some changes are carried to improve the performance of the refrigeration cycle. The operating parameters of the compressor are modified, the condensation and evaporation temperatures are readjusted adapting the operating pressures, the physical characteristics of the system are maintained, as well as the power supplied. It should be remarked that the modifications are theoretical, and for experimental operation physical changes to the installation of the domestic refrigerator would be required. However, these repairs are minor compared to the required to implement hydrocarbons [10].

Figure 4 presents the thermodynamic diagram of the refrigeration cycle for the cases studied. In case B the performance of the compressor is improved, increasing the volumetric displacement and its isentropic efficiency. In case C the operating temperatures are modified, raising the evaporation temperature by 5.3 °C and reducing the condensation temperature by 4.4 °C. All these modifications seek to improve the performance of the refrigerant in the thermodynamic refrigeration cycle.

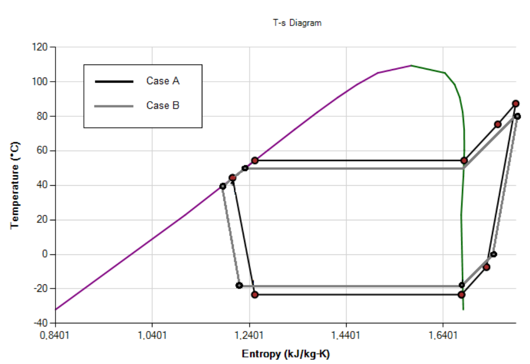


Figure 4. Improvements to the real refrigeration cycle with R1234ze, Case A and Case B, T-s Diagram

2.4. CFD study of heat transfer

In the CFD study it is analyzed what is occurring with the refrigerant in the heat exchanger that carries out the heat absorption, simulating the pass of the refrigerant through the evaporator to obtain data about phase change, temperature and behavior of the R1234ze refrigerant. In addition, it is simulated the air flow in the refrigerator with the cooling capacity supplied by the HFO, to compare with the temperatures achieved in the compartments with the R134a, which are –13° C for the freezer and 7 °C for the refrigerator, with an average operation at an ambient temperature of 18 °C.

The study is carried out in a geometric model with the dimensions of the reference refrigerator that operates with R134a. The model has a total volume of 239 l of space of the service container, between freezer and refrigerator. The evaporator consists of a pipe of copper type K with coil shape and a nominal diameter of 3/8 inches, located in the area of the freezer. The geometry of the control volume for the refrigerant in the evaporator and the control volume for the air within the refrigerator are shown in Figure 5.

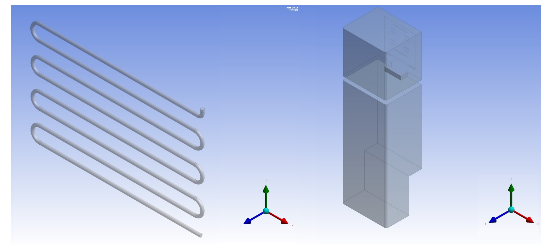


Figure 5. Geomtry of the control volume for simulation. a) Refrigerant in the evaporator. b) Air within the refrigerator

2.4.1. Mathematical models for simulation

For the surrounding air within the refrigerator, the volume of fluid model is used to simulate air circulation and temperature change. The Euler-Euler approach is utilized for the multiphase model in the evaporator, which solves the momentum and continuity equations. Two different phases that interact in the phase change are modeled, the first as liquid or liquid-vapor mixture and the second as vapor. Using the concept of volume fraction with regime equations for each phase, for the concentration of mass in the interaction of the phases it is utilized the model established by Equation 4.

$$A_i = \frac{6\alpha_p(1-\alpha_p)}{d_p} \tag{4}$$

Where:

A_i: Area of the interface
α_p: Volume fraction of phase q
d_p: Diameter of the bubble

The effects of viscosity and turbulence in the fluid are simulated with the $k-\varepsilon$ RNG model, which includes the eddy effect in the turbulence and improves the effect of the Reynolds number for the effective viscosity [18]. The model comprises expressions for each variable, Equation 5 and Equation 6.

For k:

$$\begin{gathered}\frac{\partial}{\partial r}(pk)+\frac{\partial}{\partial_{xi}}(pku_i) = \\ \frac{\partial}{\partial xj}\left(\alpha_k\mu_{eff}\frac{\partial}{\partial xj}\right)+G_k+G_b-\rho\varepsilon-Y_M+S_k\end{gathered} \tag{5}$$

For ε:

$$\begin{gathered}\frac{\partial}{\partial r}(p\varepsilon)+\frac{\partial}{\partial_{xi}}(p\varepsilon u_i) = \\ \frac{\partial}{\partial xj}\left(\alpha_\varepsilon\mu_{eff}\frac{\partial}{\partial xj}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3s}G_b)- \\ -C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon\end{gathered} \tag{6}$$

Where:

G_k: Generation of turbulence kinetic energy due to average velocity
G_b: Generation of turbulence kinetic energy due to buoyancy
Y_M: Contribution of the fluctuating expansion on the compressible turbulence at the general dissipation rate
S and C: Constants and terms defined for each variable
$R\varepsilon$: Term added in the RNG method to increase the precision
αk and $\alpha\varepsilon$: Inverse of the effective Prandtl numbers for k and ε, respectively
μ_{eff}: Effective viscosity

The conservation of energy and mass are established by means of balancing the amount of mass that gets in and the amount that gets out; for Euler model the laws that govern these parameters are defined by Equation 7 and Equation 8, respectively.

Conservation of energy:

$$\begin{aligned}&\frac{\partial}{\partial_t}\left(\alpha_q\rho_q h_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{u}_q h_q\right)\\&=-\alpha_q\frac{\partial p_q}{\partial t}+\bar{\bar{t}}_q:\nabla\vec{u}_q-\nabla\cdot\vec{q}_q+S_q+\\&+\sum_{p=1}^{n}\left(Q_{pq}+\dot{m}_{pq}h_{pq}-\dot{m}_{qp}h_{qp}\right)\end{aligned} \tag{7}$$

Conservation of mass:

$$\begin{aligned}&\frac{\partial}{\partial_t}\left(\alpha_q\rho_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{u}_q\right)=\\&\sum_{p=1}^{n}\left(\dot{m}_{pq}+\dot{m}_{qp}\right)+S_q\end{aligned} \tag{8}$$

Where:

h_q: Enthalpy specified for the secondary phase
Q_{pq}: Intensity of heat exchange between the primary and secondary phases
h_{pq}: Enthalpy of phase change
$\vec{v}_q$: Velocity of the secondary phase q
$\dot{m}_{pq}$: Mass transferred from the primary to the secondary phase
$\dot{m}_{qp}$: Mass transferred from the secondary to the primary phase

Lee model defines the mass transfer by condensation or evaporation of one phase to the other, the liquid phase is defined as the primary phase and the vapor phase as secondary depending on the conditions of the refrigerant when entering the exchanger, this model is described by Equation 9.

$$\frac{\partial}{\partial_t}\left(\alpha_p\rho_p\right)+\nabla\cdot\left(\alpha_p\rho_p\vec{V}_p\right)\dot{m}_{qp}-\dot{m}_{pq} \tag{9}$$

Where:

ρ_p: Vapor phase
$\vec{V}_p$: Velocity of vapor
$\dot{m}_{pq}$: Rate of mass transferred in evaporation
$\dot{m}_{qp}$: Rate of mass transferred in condensation

In addition, Moraga correlation is integrated in the interaction between phases to define the Lift coefficient to simulate the effects caused by the eddy produced as the fluid passes as liquid, the drag coefficient is defined by Schiller-Naumann correlation to simulate the drag in the liquid surface between phases [18].

3. Results and discussion

The thermodynamic parameters obtained in the cycle of the domestic refrigerator with R134a, used as base for the cycle with R1234ze, are shown in Table 3.

Table 3. Parameters of the refrigeration cycle with R134a

Parameter	R134a
Evaporation temp.	–23,3 °C
Overheating	18,3 °C
Condensation temp.	54,4 °C
Subcooling	8 °C
Mass flow	0,0012 kg/s
Isentropic efficiency	0,688
Power consumed	0,104 kW

With the thermodynamic tests conducted in the simulations for R1234ze and the data obtained for R134a, it may be seen that the difference in the coefficient of performance (COP) of the cycle with R1234ze is reduced compared to the cycle with R134a; Figure 6 presents these results.

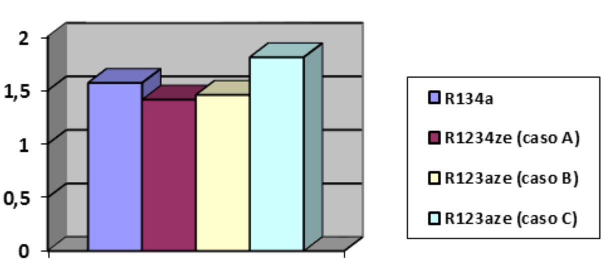


Figure 6. Coefficient of performance (COP)

The most important thing in a refrigeration system is the capacity to produce cold or to eliminate heat; for this purpose, it is calculated the cooling capacity and the heating capacity of the refrigeration cycle. Figure

7 compares these parameters for the cycle with R134a, and cases A, B and C for R1234ze.

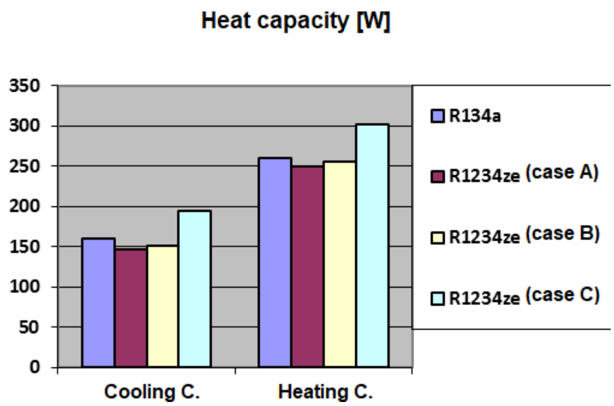


Figure 7. Cooling and heating capacity in thermodynamic cycles

It may be observed that case C has the highest heat capacity due to the modifications carried out at the operating temperatures; however, to carry out this modification it is necessary a greater energy consumption by the compressor, which would reduce the energy efficiency of the refrigerator. On the other hand, cases A and B have capacities very similar to the cycle with R134a.

Another parameter which exhibited important changes in the thermodynamic study, is the discharge temperature of the compressor. This information is useful because a large discharge temperature produces high fatigue in the compressor, and besides it is unfavorable in the thermodynamic cycle since it increases the work consumed by the compressor. Figure 8 shows the data obtained regarding temperature variation in the compressor for both refrigerants.

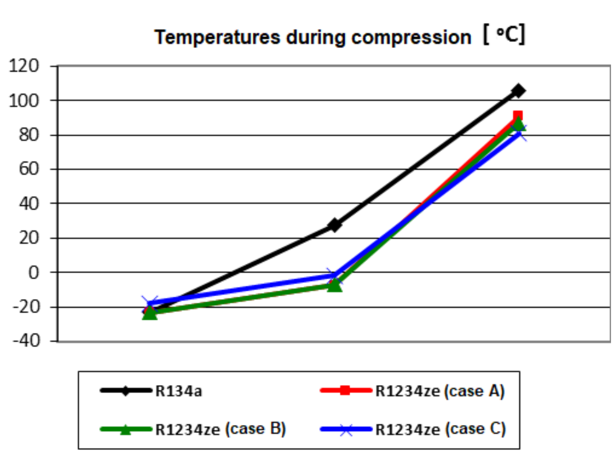


Figure 8. Temperature variation in the compression process

Due to the properties of the HFO, it generates less fatigue in the compressor because of a smaller discharge temperature, and besides it is highly compatible with various materials as opposed to hydrocarbons; this is a great advantage for HFOs in vapor compression cycles. Another important factor for the performance of the compressor is the velocity at which the refrigerant should flow. Table 4 presents the mass flow required for each cycle studied.

Table 4. Mass flow required for each cycle [kg/s]

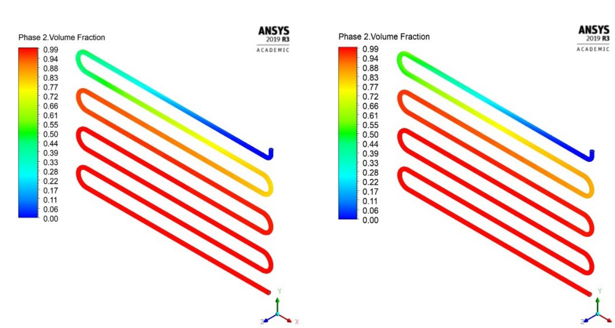
R134a	R1234ze (A)	R1234ze (B)	R1234ze (C)
0,0012	0,0013	0,0014	0,0016

3.1. Results of the CFD study

3.1.1. Refrigerant in the evaporator

In a vapor compression refrigeration cycle, the evaporator is responsible for absorbing heat, transporting it to the compressor, and then expelling it to the environment in the condenser. In this absorption process, the refrigerant experiences a phase change from liquid-vapor mixture to vapor, and the performance of the refrigerant in the process is one of the main factors that determines the cooling capacity of the cycle.

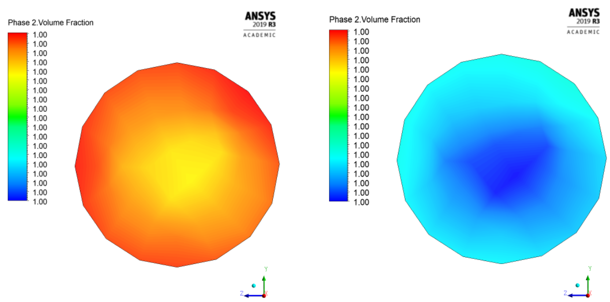
Figure 9 shows the phase change along the evaporator for the R1234ze refrigerant, to verify that the HFO accomplishes the complete evaporation in the exchanger and does not deliver wet vapor to the compressor, which may deteriorate it or produce malfunctioning during compression. The performance is compared with the refrigerant R134a, having a scale from 0 to 1 for the quality of the mixture, with 0 corresponding to the entering state (0.46 for R1234ze and 0.44 for R134a) to the evaporator as liquid-vapor mixture and 1 for saturated vapor.



(a) (b)

Figure 9. State of the refrigerant during the phase change in the evaporator. a) R1234ze, b) R134a

The characteristics of the refrigerant at the inlet of the evaporator, such as operating pressure, quality and mass flow, are given for the thermodynamic cycle previously described for each refrigerant. It may be observed that in these conditions the evaporation is similar for the two refrigerants under comparison, the R134a requires a shorter pipe length to complete the phase change; however, the HFO delivers a larger percentage of superheated vapor. Figure 10 shows a contour of average area measured at the outlet of the evaporator with the total quality of the mixture.



(a) (b)

Figure 10. Quality of the refrigerant at the outlet of the evaporator. a) R1234ze, b) R134a

Values of refrigerant temperature at the outlet of the evaporator are also obtained, Figure 11. It is observed in the results that there is overheating during heat absorption, the temperature is greater at the fluid surface in contact with the wall of the evaporator, reaching –6.83 °C in average, and remaining at the saturation temperature of –23.3 °C within the fluid.

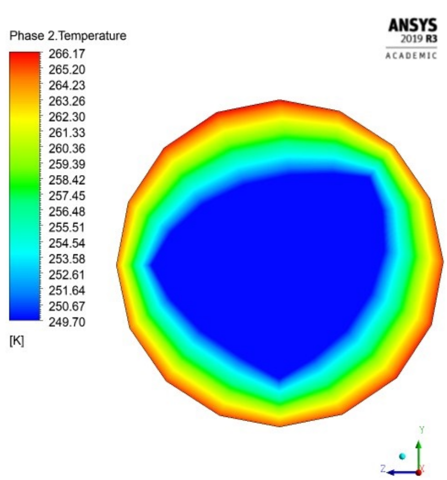


Figure 11. Refrigerant (R1234ze) temperature at the outlet of the evaporator

Compared to the HFC-134a, the HFO-1234ze reaches a higher overheating temperature at the end of the evaporation process, this variation is very small and thus it will no produce an important effect at the inlet of the evaporator. Figure 12 shows a comparison of the temperature at different points of the fluid after it leaves the evaporator.

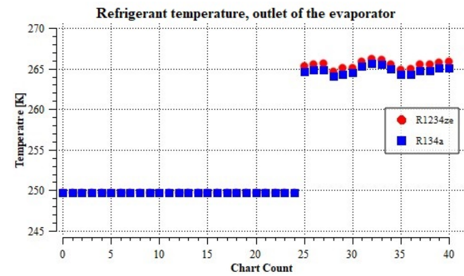


Figure 12. Comparison of overheating temperatures

The results obtained with the CFD study of heat transfer are in accordance with the results found by the thermodynamic analysis conducted in the evaporator with R1234ze; Table 5 shows the data for each case.

Table 5. Results of the studies for the evaporator

Parameter	CFD	Termodynamic study
Evaporation temp [°C]	–23,3	–23,3
Overheating temp. [°C]	–6,83	–7,3
Mass flow [kg/s]	0,0013	0,0013
Quality of the fluid	1	1
Cooling capacity [W]	146,3	146,4

3.1.2. Air flow within the refrigerator

For the air flow in the total control volume of 239 l in the compartments, 55 l for the freezer and 184 l for the refrigerator, the air circulation is simulated at an average velocity of 1.103 m/s generated by the fan of a no-frost domestic refrigerator, which operates at 2070 RPM [18]. Figure 13 schematizes the air flow within the refrigerator.

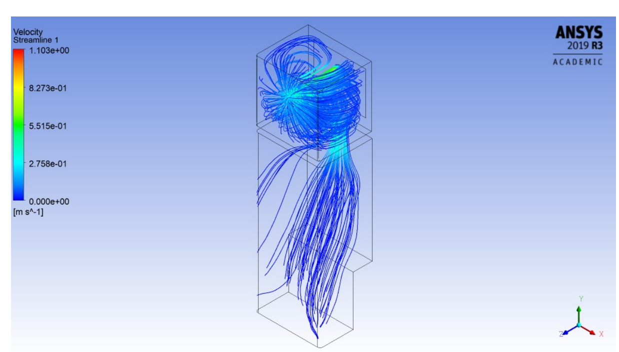


Figure 13. Air flow within the refrigerator

Tests were conducted with this flow for the cooling capacities obtained in each refrigeration cycle with R1234ze in the cases A, B and C under study. Figure 14 presents the results in a volume rendering of the air temperature, obtained with the cooling capacities for each case. Heat flows of –146.3 W for case A, –151.4 W for case B and –193.7 for case C were simulated.

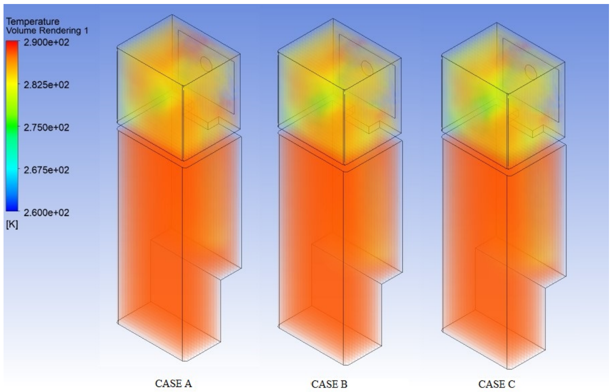


Figure 14. Volume rendering of temperature in the control volume for cases A, B and C

The temperatures reached in the freezer and in the refrigerator do not show a large variation for the three cases under study. Figure 15 schematizes the results of the temperatures at various points of the freezer, and Figure 16 the results for particles in the refrigerator.

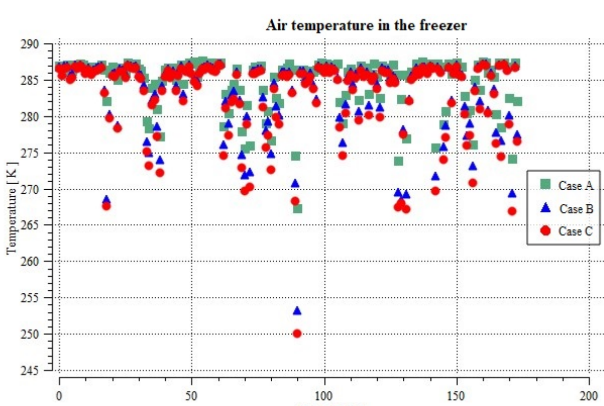


Figure 15. Comparison of temperatures in the freezer for cases A, B and C

The temperature in the freezer reaches an average value of –6 °C for case A, with peaks up to –8 °C; for case B it reaches an average value of –8 °C, with peaks up to –18 °C; and for case C with system redesign it reaches an average value of –12 °C, with peaks up to –22 °C.

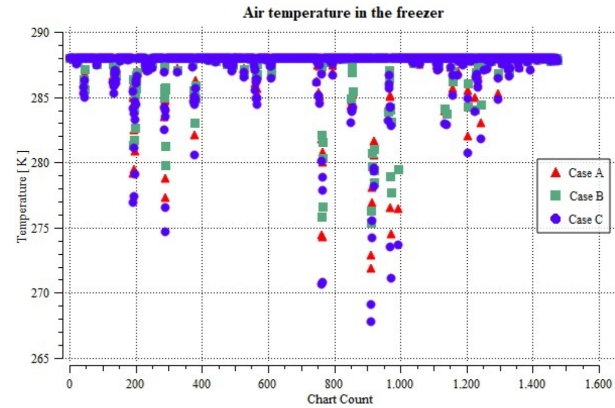


Figure 16. Comparison of temperatures in the refrigerator for cases A, B and C

The temperature in the refrigerator reaches an average value of 6 °C for case A with peaks up to 2 °C; for case B it reaches an average value of 4 °C, with peaks up to 0 °C; and for case C it reaches an average value of 2 °C, with peaks up to –4 °C. These results do not take into account losses due to air that enters when the doors are opened.

4. Conclusions

The substances of the HFO family are considered as the fourth generation of fluoridated refrigerants, due to their physical and environmental properties, and they are an excellent alternative for designing refrigeration or air conditioning systems. The HFO-1234ze is one of these alternatives, which due to its characteristics is a highly likely replacement of R134a in domestic refrigeration systems. Its contribution to global warming is 99.9% smaller than R134a and 75% smaller than R600a, the refrigerants mostly used in domestic refrigeration, and due to their characteristics of null toxicity and slight flammability, they fulfill environmental and safety regulations currently established.

With the results obtained in the thermodynamic and heat transfer tests conducted with Genetron Properties and ANSYS Fluent, besides the mathematical analysis, it may be concluded that refrigerant HFO-1234ze is suitable for working in a domestic refrigerator, showing necessary refrigeration parameters without having the environmental cost of conventional HFCs and the high flammability of hydrocarbons.

With the same operating conditions in a domestic refrigerator, the HFO has a cooling capacity only 8% lower than HFC-134a; a cooling capacity 5% lower is achieved with adaptations in the compression process, and redesigning the system for different working temperatures enables yielding a cooling capacity 20% larger; however, with this redesign the energy efficiency diminishes 2%. The coefficient of performance (COP) of the cycle is 1.57 with R134a, 1.41 with R1234ze without adjustments, 1.46 for R1234ze with improvements to the compressor and 1.8 for R1234ze with redesign.

The discharge temperature in the compressor is substantially smaller with refrigerant R1234ze compared to R134a, being 16 ºC smaller in average, which significantly favors the useful life and the energy consumption of the compressor. It could be also observed that the intake temperature does not show important variations between the two fluids, and that, in all cases, not wet vapor is delivered to the compressor. The temperatures reached, both within the freezer and within the refrigerator, are very similar to the experimental temperatures of the reference refrigerator, and thus it is expected to achieve a correct refrigeration when using refrigerant R1234ze.

When performing physical adaptations to a refrigeration system to operate with R1234ze, data about cooling capacity and operating temperatures and pressures should be considered. It is necessary to take advantage of the thermodynamic characteristics of the refrigerant in the cycle, because the refrigerant works better with higher evaporation temperatures and its properties make it better for the compression process. In future research works, it is recommended to study mixtures of HFO and HFC to totally replace the latter, without having to replace the devices that constitute the refrigeration system.

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