J Ther Eng, Vol. 10, No. 6, pp. 1453–1464, November, 2024

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000886

Research Article

Effect of refrigerant charge variation on the energy and thermal performance of a domestic refrigerator

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ARTICLE INFO

Article history
Received: 08 August 2023
Revised: 13 December 2023
Accepted: 16 December 2023

Keywords:
Domestic Refrigerator; EER; Energy; Refrigerant Charge; Temperature

ABSTRACT

Inadequate refrigerant charges can affect the vapor compression refrigeration systems' thermal and energy performance. To delve deeper into the subject, this study experimentally evaluated the performance of a domestic refrigerator operating at different refrigerant charges. Some of them simulate refrigerant leaks (70 and 80 g), and some others simulate an excess (100 and 110 g). Through a statistical analysis (Tukey test and control graphs), the temperature data with the greatest impact were analyzed, including the temperatures in the suction and in the compressor casing, the temperatures in the middle position and outlet of the condenser and evaporator, as well as the temperatures in the freezer. The operation of the refrigerator was affected to a greater extent when it worked with an overcharge of 110 g; here, the discharge pressure and the run time increased by 1.3 bar and 21%, respectively, compared to the conditions of the refrigerator operating with the reference charge (86 g). In addition, the excess charge also caused an increase in energy consumption of 0.56 kWh/day and a decrease in EER of 0.5 regarding the reference charge. Finally, the increase in energy consumption was projected to $0.03 USD per day with respect to the reference cost.

Cite this article as: Pardo-Cely D, Belman-Flores JM, Gallegos-Muñoz A, Rodríguez-Valderrama DA. Effect of refrigerant charge variation on the energy and thermal performance of a domestic refrigerator. J Ther Eng 2024;10(6):1453−1464.

INTRODUCTION

Over the course of years, the domestic refrigerator has been maintained as one of the most widely used household appliances for food preservation, preventing the growth of microorganisms that damage food and affect human health. In 2020 in Mexico, approximately 31 million refrigerators were in use, which accounted for around 29% of the energy consumption in the residential sector [1, 2]. This energy consumption is taken into consideration under normal operating conditions, but like any household appliance, the refrigerator can present problems in the functioning of its components, due to either electrical or mechanical aspects. In addition, problems can also occur due to microleaks or improper refrigerant gas charges, which could affect the

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This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University Press, İstanbul, Turkey

thermal and energy performance of a refrigeration system [3, 4]. Thus, timely detection of improper operation in vapor compression refrigeration systems could help improve system performance as well as minimize unwanted environmental effects [5].

The evaluation of the amount of refrigerant in vapor compression systems is one of the main areas of study due to the effect it has on the energy performance of the system [6, 7], as well as the thermal performance according to the application of the refrigeration system. In this sense, in literature, there are experimental and theoretical works that allow for determining the causes for which refrigerant leaks occur. Li et al. [8] concluded, for instance, that refrigerant leaks are caused by prolonged operation of the refrigeration system, either by continuous vibrations in the pipeline or by corrosion inside the pipeline causing different types of cracks and holes. In most cases, the refrigerant leak is located at the joints of the valves and pipeline, at the elbows of the heat exchanger coils, and in the high-pressure liquid line [9]. On the other hand, a refrigerant overcharge can occur when the refrigeration system is charged with more refrigerant than those recommended by the manufacturer as a result of maintenance [10] or even due to a lack of calibration in the process and assembly line.

Du et al. [11] investigated a refrigeration system working with inadequate refrigerant charges (overcharge and leak), and some of their results showed that refrigerant overcharging caused a decrease in the normalized coefficient of performance, COP. On the other hand, when there was a 20% refrigerant leak, it was observed that the temperature at the condenser outlet presented the greatest variation. Grace et al. [12] studied the performance of a vapor compression system when the R404A refrigerant charge varied from its design value (25% below and 25% above). The results showed that the COP did not present significant changes when the refrigerant charge was within a range of ± 25% of the design value. On the other hand, the COP decreased by 45% when the charge was below 25% and decreased by 13% for a refrigerant charge greater than 25%. In addition, the refrigerant overcharge caused the discharge pressure to increase significantly; otherwise, it happens with the suction pressure, where there were no significant changes for the different levels of refrigerant charge. Deymi-Dashtebayaz et al. [13] found that by optimizing the refrigerant charge, it was possible to save 785 GWh of energy consumption per year in the residential sector. The above when evaluating the effect of the charge of R22 from 540 g to 840 g in a split type of air conditioner.

On the other hand, Kim and Kim [14] studied the cooling capacity of a refrigeration system working with different refrigerant charges. The authors concluded that the subcooling gradually decreased as the refrigerant overcharge condition increased due to the accumulation of refrigerant at the outlet of the condenser. Lee and Chang [15] proposed a method in which the amount of refrigerant and the detection of refrigerant leaks can be predicted based on the starting characteristics of the air conditioner. Besides that, artificial intelligence has also been used to detect refrigerant leaks in real time. For example, Tassou and Grace [16] used neural networks for refrigerant leak detection; one neural network was used to predict the compressor discharge pressure and the other to predict the temperature of the refrigerant in the evaporator. With this, the system had the ability to detect small refrigerant leaks when the charge dropped below 33% of the nominal refrigerant charge. Yang et al. [17] used 35 fault identification rules for refrigerant leaks, considering a maximum leak of 30% of the rated charge. The results showed an accuracy of 91% in fault identification through these rules. Boeng and Melo [18] experimentally studied the thermodynamic behavior of a domestic refrigerator (factory refrigerant charge of 47 g) for refrigerant charges of 36.7 g and 64.7 g. Among the results, the authors concluded that as more refrigerant is added, it accumulates in the heat exchangers, increasing condensation and evaporation pressures, ultimately causing an increase in energy consumption of up to 30%. Gugulothu [19] evaluated the refrigeration effect by means of a design of experiments, varying three parameters, including refrigerant charge (86 g, 96 g, and 106 g). The results showed that when the refrigerator works with a refrigerant charge of 96 g, it shows a lower energy consumption and a better COP.

As mentioned above, the variation of refrigerant charge in refrigeration systems based on vapor compression affects to some extent the energy and thermal performance of the system. Thus, the objective of this work is to evaluate the thermal and energy performance of a domestic refrigerator experimentally when it works with inadequate refrigerant charges, that is, charges below and above the optimum charge (86 g of R516A) [20], simulating leaks and excess refrigerant. As a novelty, the use of control graphs is proposed to better map and understand thermal behavior (refrigerant side and internal compartments) of the refrigerator under the operation of different refrigerant charges, the application of a statistical analysis is proposed. The foregoing with the purpose to evaluate the energy performance of the refrigerator according to those parameters that present greater thermal variation. Among the main results discussed are the EER, energy consumption, compressor power, and cost of energy consumption due to charge variation.

EXPERIMENTAL METHODOLOGY

The experimental system used to carry out this study consists of a domestic refrigerator, a data acquisition system, and an energy analyzer. The domestic refrigerator is from the Mabe brand with a volumetric capacity of 0.51 m^3; it uses R516A as a low GWP alternative refrigerant and has a 280 W resistive element for automatic defrosting. It also has two fans, one attached to the condenser (forced convection heat dissipation) and another internal attached to the evaporator, which moves the flow of cold air inside the food

Table 1. Measurement uncertainty in sensors

Sensors	Measurement sensitivity	Precision
Type K thermocouples	42 μV/°C	± 0.7 °C
Pressure transducers	0 a 13.78 bar	< ± 0.5 % span
Fluke 438–II		± 3%

compartments. The compressor motor is 0.74 kW with a fixed speed, Embraco model EM3Y50HLP and a working voltage of 127 V at a 60 Hz frequency.

Experimental System Instrumentation

The refrigerator was instrumented to obtain the changes in thermal and energetic performance for the different charges of refrigerant R516A. Type K thermocouples were used for temperature measurement; these thermocouples were connected to a temperature module NI-9213 (operating temperature range of -40 °C to +70 °C). For the measurement of working pressures, suction pressure, and discharge pressure, two pressure transducers were used, which were connected to the NI-9207 module. Both the temperature and pressure sensors were connected to a NI cRIO-9030 chassis model and a computer with drivers and LabView SignalExpress. Power consumption was measured using a Fluke 438–II power quality analyzer. Table 1 shows the sensitivity and precision of the measurement made by the sensors used.

Figure 1 shows schematically the detail of the instrumentation of the different components of the refrigerator (condenser, evaporator, and compressor) as well as the internal compartments (freezer and fresh food compartment). The measurement points and the location of the temperature and pressure sensors are shown in blue, as shown in the following figure. For the condenser and evaporator, the refrigerant temperature was measured at points such as the inlet, in the middle position, and at the outlet with respect to the length of the heat exchanger. For the compressor, the temperature and pressure at the suction and discharge, as well as the casing, were measured. The air temperature inside the internal compartments of the refrigerator was also measured, with three measurement points determined within each compartment. Copper masses were used for the temperature measurements in the compartments, as specified by NOM-015-ENER-2018.

The experimental tests were carried out under the following operating conditions:

- Without food charge in the compartments and behind closed doors.
- Testing started when the freezer and the fresh food compartment were at the same ambient temperature.
- All the tests were carried out in a space where the ambient temperature was 32 °C ± 1.5 °C and the relative humidity of 40 ± 5%.
- The thermostat level was set to position 3 (the middle position as shipped from the factory).
- Data was recorded every 10 seconds for all temperature, pressure, and energy measurements.
- 7 test hours were defined for each refrigerant charge in stable thermal conditions.
- A replication was performed for each of the tests for data reliability purposes, thus obtaining an average for the parameters analyzed.

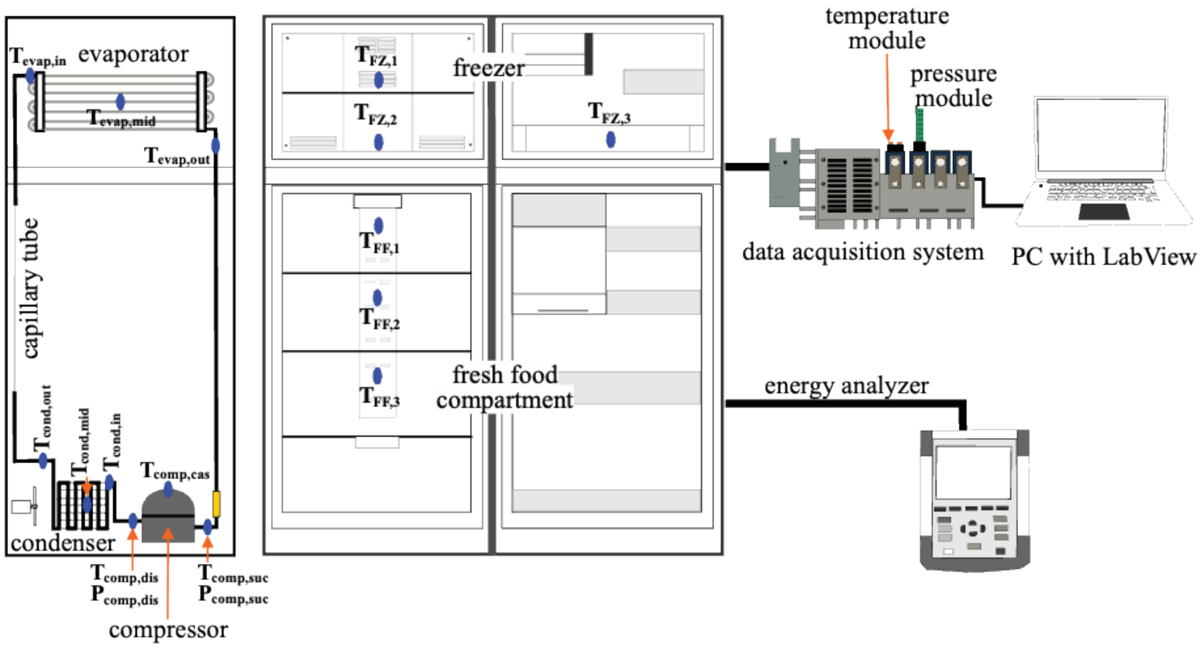

Figure 1. Schematic instrumentation of the experimental refrigerator.

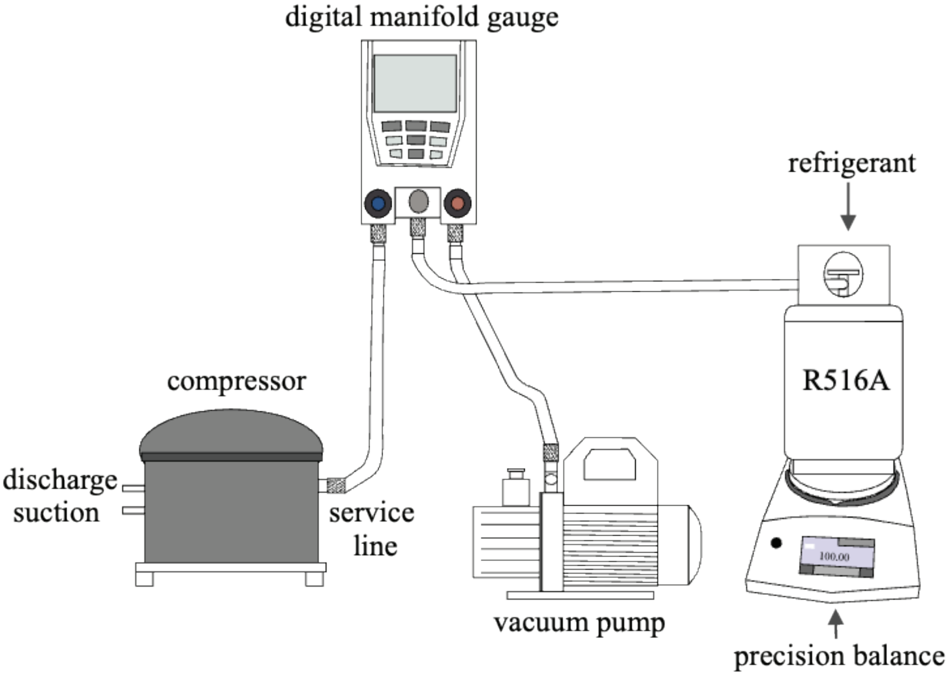

Figure 2. Schematic process of refrigerant charge.

Case Study

Figure 2 shows schematically the vacuum and refrigerant charging process, which involves a digital manifold gauge, an analytical balance, and a vacuum pump. In this case, the refrigerator works with the azeotropic mixture R516A. A vacuum process was carried out for each refrigerant charge using a 0.37 kW vacuum pump (rotation speed of 2800 rpm, voltage of 110 v, and frequency of 60 Hz). A testo 550 brand digital manometer is used, which is connected to the compressor service line, to the vacuum pump, and to the refrigerant tank, which is located on a digital scale, to observe and record the refrigerant charge that enters the refrigerator.

Initially, the refrigerator was evaluated with an optimum charge of 86 g for the refrigerant R516A, as established in the experimental work of Belman-Flores et al. [20], where the optimal charge was determined by the lowest energy consumption. Based on this charge, two refrigerant charges were proposed below (simulating a refrigerant leak) and two charges above (simulating an excess of refrigerant). Refrigerant overcharging may occur during maintenance, where the service technician may charge the system with more refrigerant than recommended by the manufacturer [10]. The different charges proposed in this work are presented in Table 2.

Table 2. Evaluated R516A refrigerant charges

Conditions evaluated	Charge [g]
Optimum charge (reference)	86
Simulating a refrigerant leak	70
	80
Simulating an overcharge	100
	110

RESULTS AND DISCUSSION

This section presents the thermal behavior and energy performance of the domestic refrigerator under different refrigerant charge conditions. First, all the temperature measurements are evaluated using the Tukey method to focus the statistical analysis on those temperature points that present greater variability for the different refrigerant charges. Thus, the measured points that represent significant variations with respect to the performance of the reference refrigerator (86 g optimum charge) are identified. According to this first study, a statistical analysis is proposed using control charts, which show the impact of the variation in the refrigerant charge on the operation of the refrigerator. The operation is also projected on a *P-h* diagram, and power consumption and energy efficiency performance (EER), are discussed. Finally, an energy cost analysis is shown for the different refrigerant charges.

Data Analysis Using the Normal Distribution and the Tukey Method

The measurements of the 15 temperature points (Fig. 1) are initially analyzed for the optimum charge since these data represent the normal behavior of the refrigerator; thus, they are used for checking if they follow a

Table 3. Statistics of the temperature data for the reference charge (86 g)

Measuring point	Mean (°C)	Standard deviation σ	p
$T_{comp,suc}$	32.39	0.84	0.64
$T_{comp,cas}$	62.10	3.10	0.19
$T_{comp,dis}$	69.40	8.36	0.33
$T_{cond,in}$	50.92	6.11	0.45
$T_{cond,mid}$	39.93	2.24	0.45
$T_{cond,out}$	38.94	2.14	0.61
$T_{evap,in}$	-21.52	2.08	0.46
$T_{evap,mid}$	-22.59	2.07	0.36
$T_{evap,out}$	-21.89	2.06	0.27
$T_{FZ,1}$	-22.45	1.00	0.06
$T_{FZ,2}$	-21.51	0.62	0.98
$T_{FZ,3}$	-20.70	0.69	0.16
$T_{FF,1}$	3.30	0.29	0.10
$T_{FF,2}$	2.13	0.30	0.09
$T_{FF,3}$	1.90	0.24	0.20

normal distribution. For this, the hypothesis method was used, which defines that if the P-value is less than the significance level (α=0.05), the data does not follow a normal distribution. Table 3 shows that the P-value for all the measured data is greater than the significance level; therefore, the data obtained for the optimum charge follow a normal distribution.

All the temperature measurements for the different refrigerant charges were analyzed in order to evaluate the variability of the data and conclude which are most affected by the different refrigerant charges. Using the Tukey test, we can compare the difference between the mean and a critical value [21]. Equation (1) was used to find the calculated Tukey value (T_α).

$$T_\alpha = Q_\alpha(k, N-k)\sqrt{\frac{MS_E}{n_i}} \quad (1)$$

Where, Q_α (k, N - k) is the standardized range and its distribution obtained from the table [22], n_i is the amount of data in each sample, N is the total number of elements comprising all the samples, and k is the number of groups of the samples being compared. MS_E is the value of the mean square of the error obtained by the equation (2).

$$MS_E = \left(\frac{SS_E}{N-k}\right) \quad (2)$$

SS_E is the sum of squares of the error, equation (3).

$$SS_E = SS_T - SS_{trat} \quad (3)$$

SS_T is the sum of total squares, and SS_{trat} is the sum of squares between treatments, and they are obtained by the equations (4) and (5).

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n}\left(y_{ij} - \bar{y}_{..}\right)^2 \quad (4)$$

$$SS_{trat} = n\sum_{i=1}^{a}(\bar{y}_i - \bar{y}_{..})^2 \quad (5)$$

Where, y is the experimentally measured value, $\bar{y}$ is the average of the measured values.

A significant difference occurs when the discrepancy between means is greater than the calculated Tukey value. In this case, the means of the distinct refrigerant charges were compared (μ70, μ80, μ100 and μ110) with regard to the mean of the optimum charge (μ86). Table 4 shows the differences in the averages of each refrigerant charge concerning the average of the reference charge. Additionally, the calculated Tukey value is presented, where the numbers shown in red are the data that represent a significant difference. For example, the value of 4.49 corresponds to the suction temperature; it exceeds the calculated Tukey value of 1.46, which indicates that the refrigerant temperature in the compressor suction is affected when the system works with a refrigerant overcharge (110 g). On the contrary, the discharge temperature did not present values that exceeded the calculated Tukey value; consequently, the discharge

Table 4. Tukey test for refrigerant charge variation and discrepancy analysis

Measuring point	Calculated Tukey	Average difference R516A (μ86)			
	T_α	μ70	μ80	μ100	μ110
$T_{comp,suc}$	1.46	0.22	0.66	1.32	4.49
$T_{comp,cas}$	3.09	0.37	0.17	4.27	7.34
$T_{comp,dis}$	8.27	0.22	1.45	5.71	3.17
$T_{cond,in}$	5.64	1.03	0.49	1.84	2.66
$T_{cond,mid}$	2.32	0.48	0.21	1.14	4.43
$T_{cond,out}$	2.26	0.34	0.22	0.36	4.08
$T_{evap,in}$	1.82	0.84	0.43	0.98	1.04
$T_{evap,mid}$	1.82	0.96	0.28	0.45	3.85
$T_{evap,out}$	1.48	3.98	1.92	1.32	3.21
$T_{FZ,1}$	1.05	1.33	0.04	0.33	4.23
$T_{FZ,2}$	0.70	1.19	0.01	0.58	3.91
$T_{FZ,3}$	0.54	1.41	0.21	0.82	3.83
$T_{FF,1}$	0.72	0.18	0.12	0.70	0.24
$T_{FF,2}$	0.90	0.10	0.08	0.84	0.05
$T_{FF,3}$	0.29	0.15	0.02	0.11	0.07

temperature in the compressor is discarded for a more detailed analysis. This behavior is similar to the findings by Li et al. [23], where the suction temperature presented greater sensitivity to excess refrigerant charge than the discharge temperature. Thus, the Tukey test initially allows for focusing the evaluation of the temperatures measured on the points that are really affected by the variation of refrigerant charge.

Thermal Analysis for Refrigerant Charge Variation

The effect of the variation of the refrigerant charge in a domestic refrigerator with respect to the optimal charge is presented in a visual and detailed way through individual control charts. According to the Tukey test, the temperatures that showed the greatest effect between the different refrigerant charges are in the compressor suction, compressor casing, middle position, and outlet of the condenser and evaporator, along with the three freezer measurements.

The methodology and equations to estimate the control limits and the mean for the individual control charts are the same as those presented in the work of Pardo-Cely et al. [24]. Figure 3 shows the temperatures around the compressor, suction, and casing by means of control graphs for the reference charge (optimal) and the other charges that simulate a refrigerant leak or overcharge. The figure also shows the upper and lower control limits (blue dotted lines), which were estimated to have three standard deviations. The red line is obtained from the mean of the reference data (optimum charge); each black point represents the average temperature measured every hour during 7 hours in a stable state, where for each test with its corresponding replicate an overall of 14 points were obtained. The orange points represent the temperature value that exceeds the control limits, indicating improper operation of the domestic refrigerator.

Figure 3 shows that the temperature measured within the compressor casing tends to move away from the central value and approach the lower control limit when there is an excess refrigerant charge compared to the optimum charge. However, none of the points surpass the lower control limit, which indicates that an excess of refrigerant does not affect the temperature in the compressor casing. This is convenient since high temperatures around the compressor affect the stability of the lubricants and internal components of the compressor [25]. On the other hand, the temperatures measured in the suction of the compressor present lower points outside the control limits for a refrigerant charge of

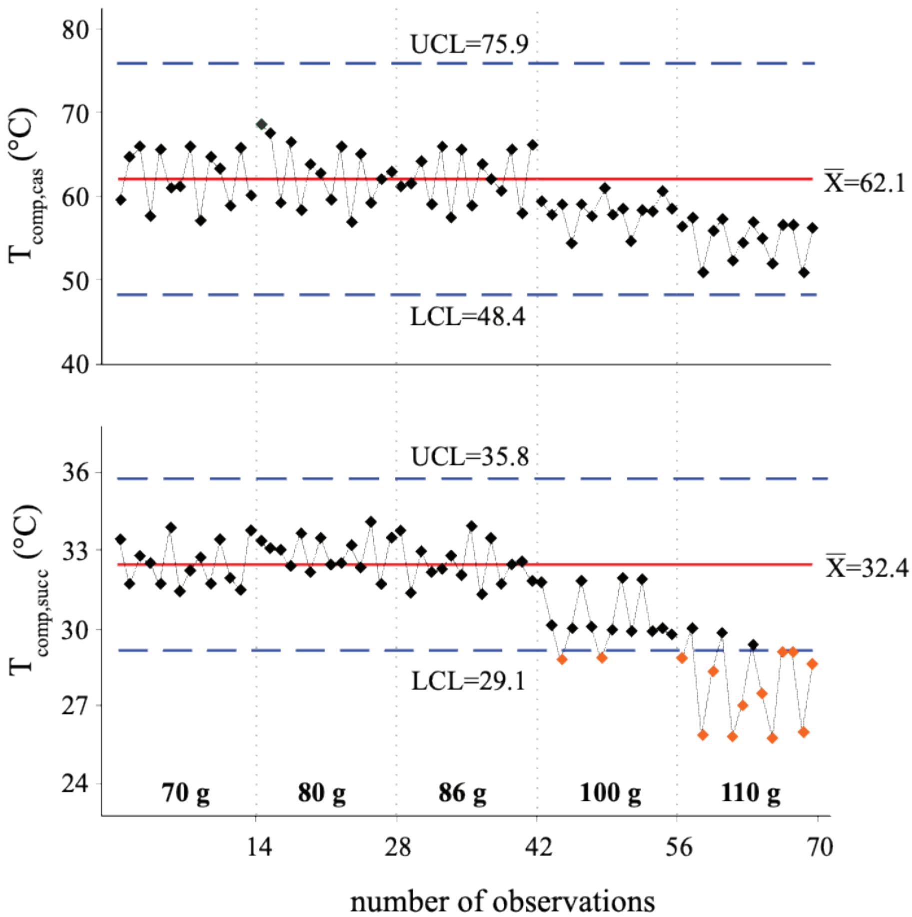

Figure 3. Suction and compressor casing temperature.

100 g, moving away from the reference average by approximately 2.1 °C. For the 110 g charge, several points outside the range indicate inadequate compressor performance for the suction temperature, which deviated from the mean temperature by approximately 4.5 °C. This behavior reflects the fact that an overcharge of refrigerant in the refrigerator represents a reduction in the suction temperature. This is due to the fact that the refrigerant does not evaporate sufficiently in the evaporator causing it to flow through the suction line towards the compressor in the liquid phase.

According to the Tukey test, the refrigerant temperature measured both in the condenser in the middle position and at the outlet presented a significant difference, therefore, a more detailed analysis was carried out using the control chart. The thermal behavior of these positions is presented in Figure 4, which shows that for the refrigerant charge of 110 g, there is a notable difference with respect to the reference temperature for the middle position and at the condenser outlet of approximately 4 °C. This increase in temperature is because the refrigerant accumulates in the condenser and therefore decreases the capacity of heat dissipation to the environment in the condenser; the same behavior is presented in the work of Bellanco et al. [10]. However, this behavior does not definitively represent a malfunction because the increase in temperatures is not outside the control limits.

The excess refrigerant leads to its accumulation in the evaporator causing an increase in the average temperature of the refrigerant in the middle position and outlet of the evaporator as shown in Figure 5. The charge of 110 g causes an increase of 3 °C in the refrigerant temperature in these positions with respect to the 86 g charge. It can also be seen that for a low refrigerant charge (70 g), the temperature at the evaporator outlet moves away from the reference average; this refrigerant charge is insufficient for the correct operation of the evaporator. In conclusion, the analysis through the control charts does not indicate an inadequate operation in the evaporator as such since the data remains within the established control limits.

Maintaining the proper temperatures in the internal compartments is ultimately the purpose of a domestic refrigerator. For example, according to the food safety guide, it is recommended that temperatures be less than 4.4 °C in the food compartment and below -17.8 °C in the freezer [26]. Figure 6 presents the temperatures measured inside the freezer compartment for the different

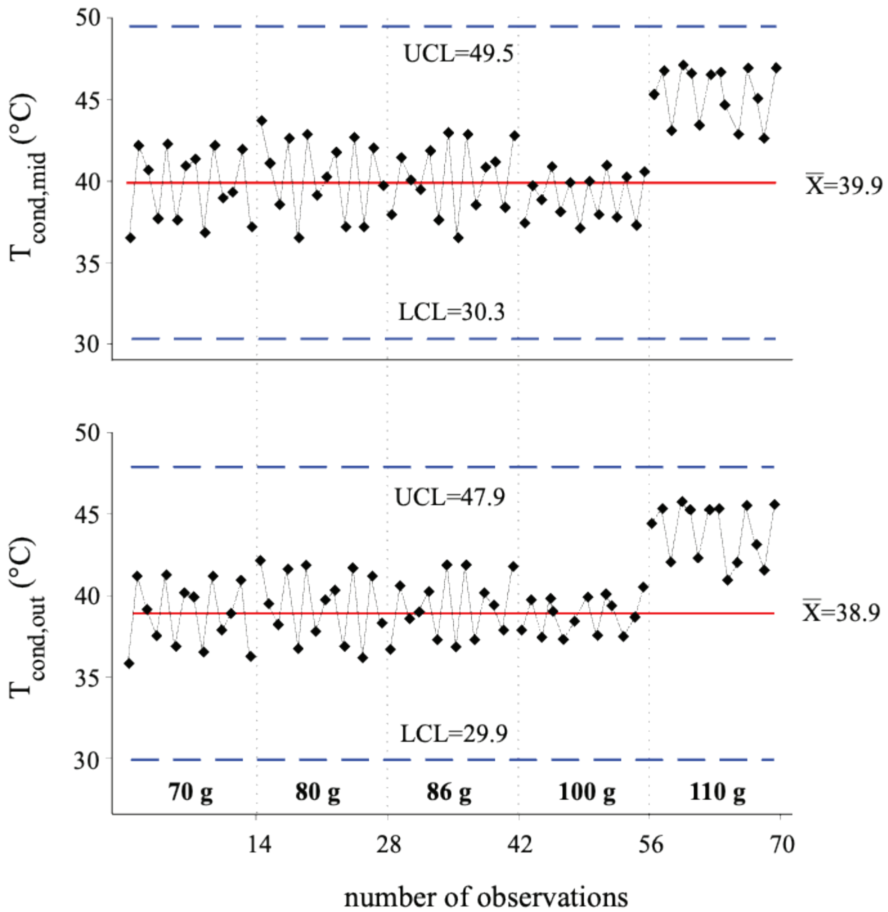

Figure 4. Temperature in the middle position and at the condenser outlet.

refrigerant charges. Through a quick inspection of the figure, it is observed that, for a refrigerant charge of 70 g, the temperature in the freezer shows points that slightly deviate from the reference mean. This condition occurs because the space where the thermocouple is located represents the hottest point for the refrigerator under study. For an excess charge (110 g), the average temperature presents a discrepancy concerning the reference average of approximately $T_{FZ,1}$=3.9 °C, $T_{FZ,2}$=4.0 °C y $T_{FZ,3}$=4.1 °C, evidencing an increase in the temperature inside the freezer, exceeding the upper control limits, which could affect the proper preservation of food.

P-h Diagram

The use of the *P-h* diagram allows to easily observe the difference between a normal operation and an inadequate one of the refrigeration system [23]. Thus, in Figure 7 the refrigeration cycle is presented in a *P-h* diagram simulating the leak and excess refrigerant. The figure shows that for refrigerant charges (80 and 100 g) very close to the reference charge, the *P-h* diagram shows minimal variation in thermodynamic properties. On the contrary, the refrigerant excess (110 g) causes a discharge pressure increase of approximately 1.3 bar, because when the refrigerant charge increases, it is stored in the condenser, causing a significant increase in pressure.

Energy Consumption

Figure 8 shows the ON/OFF operation cycle of the refrigerator during the thermal stabilization period for the different refrigerant charges. From the figure, the compressor start-up time increases for the different charges evaluated with respect to the start-up time with the optimum charge, presenting a longer time for the 110 g refrigerant charge, around 37.4 minutes, followed by 13.4 minutes for the 70 g charge, 6.7 minutes for the 80 g charge, and finally approximately 2.1 minutes for the 100 g. On the other hand, the compressor shutdown time in the cycle is approximately 23.5 minutes for the different refrigerant charges. Additionally, the run time for the reference charge is 64%, and the charges near the reference charge do not present a significant variation; the opposite is the case for the 70 g charge, where the run time is 67%, and 78% for the 110 g charge. Therefore, these last two refrigerant charges lead to higher energy consumption.

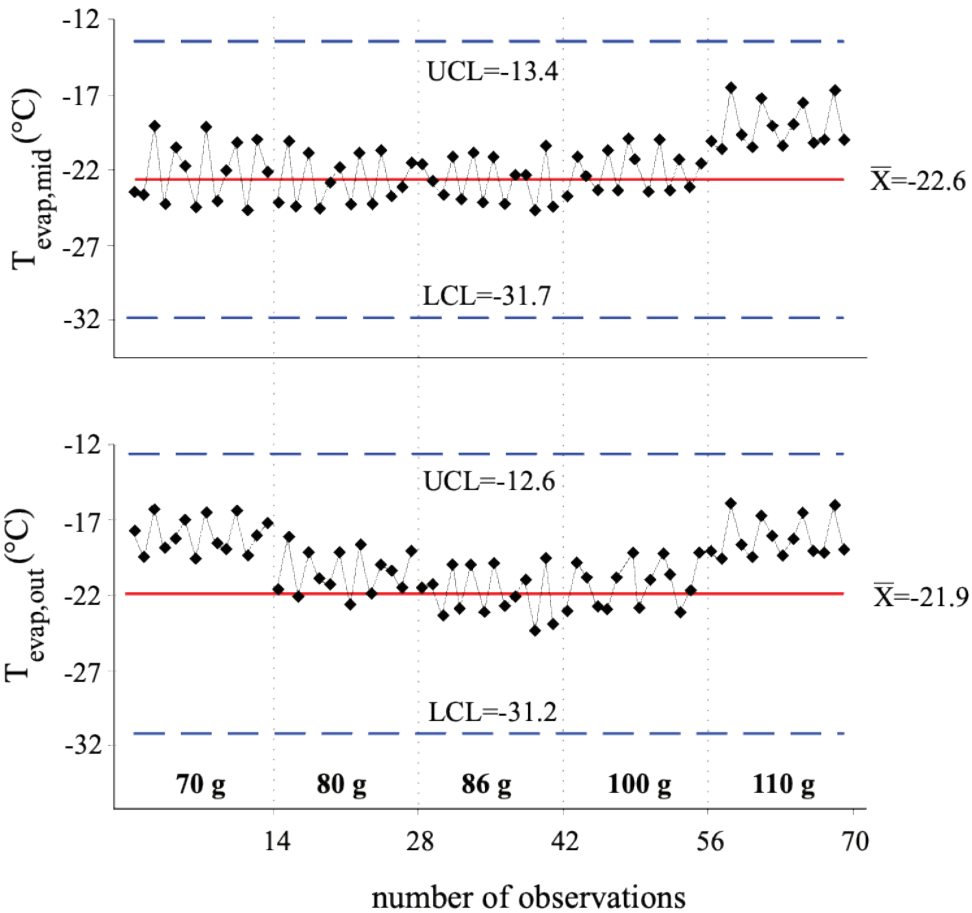

Figure 5. Temperature in the middle position and at the outlet of the evaporator.

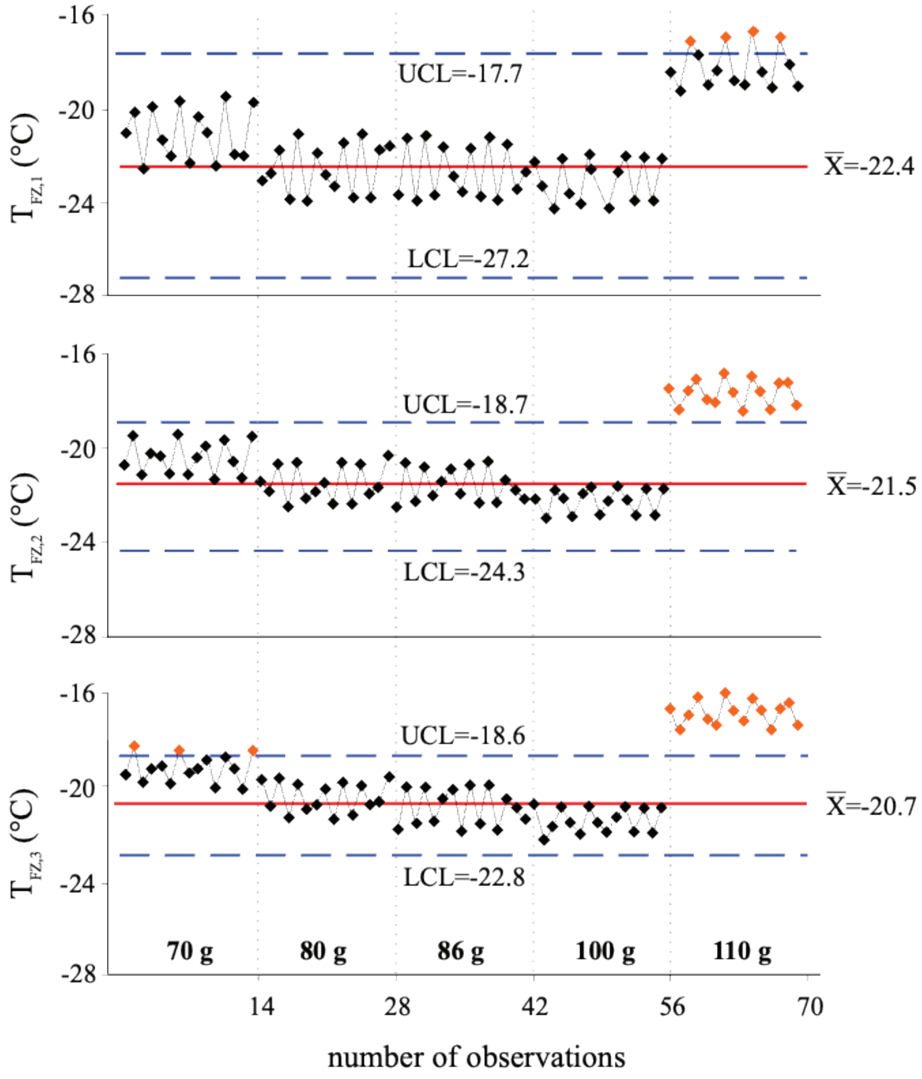

Figure 6. Temperatures inside the freezer.

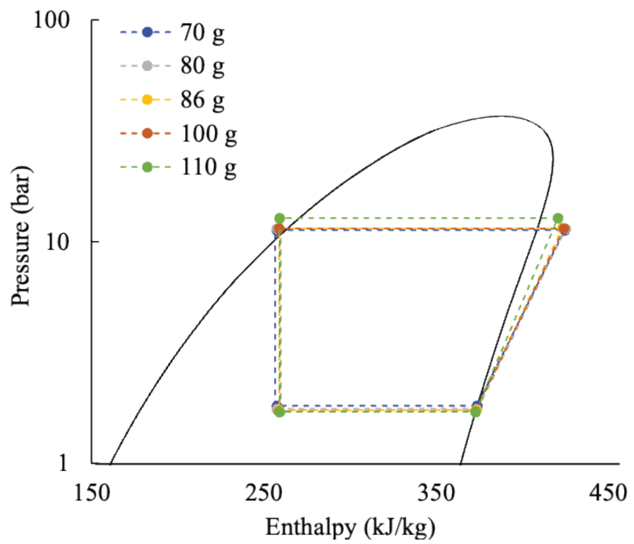

Figure 7. *P-h* diagram for refrigerant charge variations.

Another parameter of interest in showing the effect of the refrigerant charge variation is the energy efficiency ratio (EER), of the refrigeration system, which is obtained through equation (6).

$$EER = \frac{cooling\ capacity}{total\ power} \tag{6}$$

Thus, Figure 9 shows the energy consumption and EER for 24 hours of refrigerator operation under the different refrigerant charges. A quick inspection shows that the reference charge (86 g) has the lowest energy consumption and the highest energy efficiency. The opposite is true for the charge of 110 g where the greatest increase in energy is evident, around 0.56 kWh/day, and an EER of 1.3 less than the optimum charge. 70 g of charge shows an EER decrease of 0.7 and an energy increase of 0.15 kWh/day concerning the optimum charge. As for the 80 g and 100 g charges, they

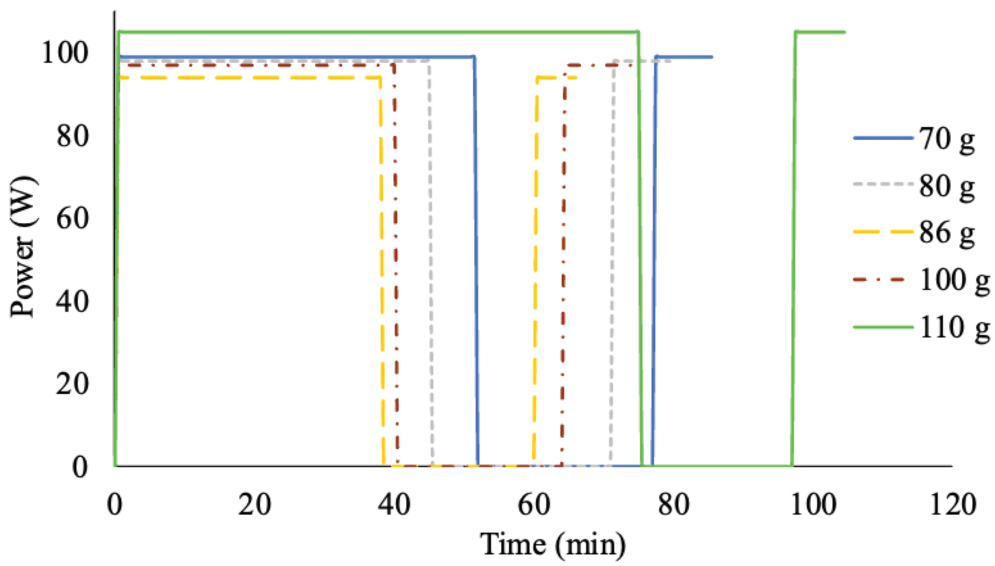

Figure 8. ON/OFF cycles of the compressor in stable conditions.

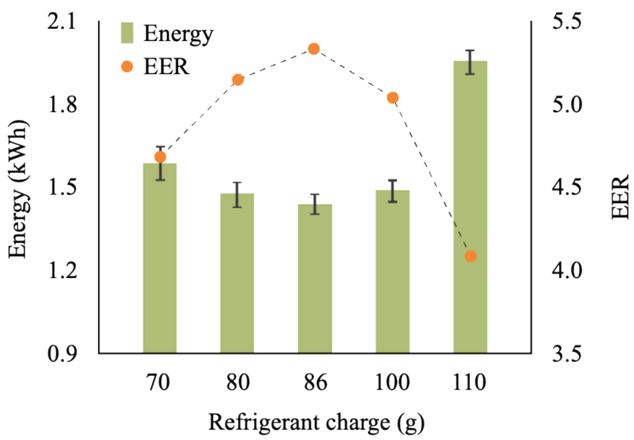

Figure 9. Energy consumption and EER for the different refrigerant charges.

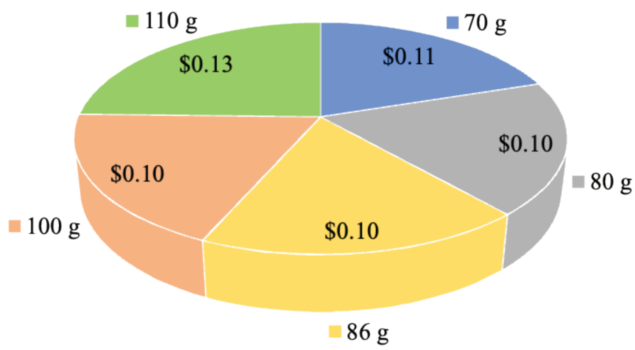

Figure 10. Cost of energy in USD per kilowatt-hour per day.

remain very close to the energy consumption of the optimal charge, increasing by approximately 0.04 kWh/day. In summary, the domestic refrigerator is affected in a greater proportion, energetically speaking, when the system works with an excess of refrigerant as well as when there is a decrease in charge.

The results obtained in this study are for a particular design of domestic refrigerator that operates with an alternative refrigerant. However, it would be expected that the results (trends) shown in this work would be similar to other refrigerator designs evaluated but in a different order of magnitude, logically due to the same thermophysical properties of the refrigerant and the different designs of components of the vapor compression cycle.

Finally, it is the user who assumes the cost of energy when the domestic refrigerator works with a certain amount of inadequate refrigerant charge; for this reason, Figure 10 presents a projection of the daily cost of energy consumption for the different refrigerant charges evaluated in this work. There is an energy cost increase of $0.03 USD per day over the baseline cost (86g optimal charge) for the 110g charge. This energy cost would increase in homes because the refrigerator in real operating conditions works with a charge of food; therefore, the compressor would work more to maintain proper thermal conditions in both compartments.

In Mexico, approximately 31 million refrigerators are in operation; if most of them had an excess of refrigerant, the cost of energy would increase by approximately $930,000 USD per day.

In this section, it has been shown graphically and simply that a refrigerant overcharge causes a considerable increase in temperature in the freezer, so this could affect the ideal conditions for food preservation. Because of this, the compressor stays on longer, causing a considerable increase in energy consumption, consequently, the user is ultimately the one who assumes the increase in energy cost. Therefore, the results of this study show the energy performance of the refrigerator, which could serve as a guide for an adequate charge of refrigerant, especially in maintenance conditions.

CONCLUSION

In this work, the impact on the operation of a domestic refrigerator when working with inadequate refrigerant charges was estimated through statistical analysis. Different refrigerant charges were evaluated experimentally; the charges of 70 g and 80 g represented a refrigerant leak, and the charges of 100 g and 110 g represented an excess of refrigerant. According to the results, the charge conditions (leakage or overcharge) near the optimal charge (86 g) did not present significant changes in the general functioning of the domestic refrigerator.

On the other hand, the negative effects were presented for the charges of 70 g and 110 g. The 70 g charge generated an increase in the temperature in the freezer for the door position of 2.2 °C; the run time increased by 0.5%, causing an increase in energy consumption of 0.15 kWh/day; and the EER decreased by 0.7 with respect to the optimal charge. The refrigerant overcharge of 110 g presented a greater effect on the suction temperature, moving away from the reference temperature by 4.5 °C, and the temperatures measured in the freezer moved away from the reference temperature by approximately 4 °C; the discharge pressure increased by 1.3 bar; and the run time increased by 21% regarding the run time of the reference charge. Consequently, these behaviors caused an increase in energy consumption of 0.56 kWh/day and a decrease in EER of 1.3 concerning the optimal charge. Finally, this increase in energy consumption caused an increase in the energy cost of $0.03 USD per day with respect to the reference cost.

NOMENCLATURE

EER	Energy Efficiency Ratio
GWP	Global Warning Potential
h	enthalpy [kJ/kg]
P	pressure [bar]
T	temperature [°C]

Abbreviations and subscripts

cas	casing
comp	compressor
cond	condenser
dis	discharge
evap	evaporator
FF	fresh food compartment
FZ	freezer
in	inlet
LCL	lower control limit
mid	middle
out	output
suc	suction
UCL	upper control limit
$\bar{X}$	center line (mean of data)
1, 2, 3	thermocouple location

ACKNOWLEDGEMENT

We acknowledge the University of Guanajuato for their sponsorship in the realization of this work.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

ETHICS

There are no ethical issues with the publication of this manuscript.

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