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Simulation of faults in domestic refrigerators of different volumetric capacity: Effect on thermal and energy behavior

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Abstract

The present study compares the thermal and energy performance of refrigerators with varying volumetric capacities when faults occur. Simulated faults include the malfunction of the fan attached to the evaporator and the airflow return area obstruction in the freezer. The proposal above included three intensity levels for each fault. Both refrigerators were instrumented to measure temperature conditions within the fresh food compartment and the freezer. In addition, during the test period, energy consumption was measured until thermal stability was reached in both compartments. The effect of each fault's levels was compared with the reference condition for each refrigerator, which was without faults, as they left the factory. The results show that the fan fault caused the most significant variation in the thermal condition of both refrigerators. The temperature increased from 2°C to 4°C in the fresh food compartment, and from 1°C to 14°C in the freezer. The above causes warmer spaces compared to the reference refrigerator. Consequently, each refrigerator's energy consumption increased from 36% to 65%.

Keywords: Domestic refrigerator; Energy; Fault; Temperature

1. Introduction

The refrigerator is one of the most essential home appliances, allowing fresh food to be preserved for extended periods. Most of these appliances are based on vapor compression technology, resulting in high energy consumption. In Mexico, according to the Census Information Consultation System (SCINCE), 87.6% of homes have a refrigerator, which represents around 32 million appliances in use [1]. According to the Federal Electricity Commission (CFE), 30% of the total energy consumption in the home is due to the use of the refrigerator.

On the other hand, it is well known that the quality and freshness of food depend on the proper thermal conditions within the refrigerator compartments, which, in turn, depend on the airflow distribution, thus, reflecting in energy consumption. Additionally, system faults due to (mechanical) breakdowns or daily use can affect the thermal and energy performance of the refrigerator. These faults can generally represent an increase in energy consumption, affecting the refrigerator's performance [2].

In the literature, some works analyze faults or usage habits in refrigerators. These can cause changes in the thermal or energy conditions of the appliance [3,4]. For example, Afonso and Castro [5] evaluated magnetic seals' wear on refrigerator doors. They found that the increase in air infiltration due to considerable wear on the magnetic seals caused

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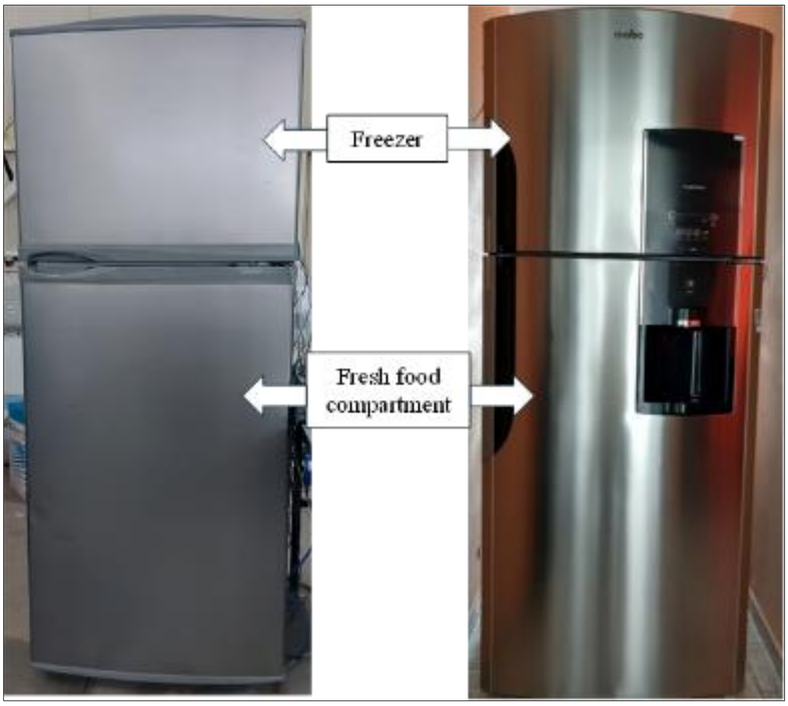
a 341% increase in energy consumption. Bassiouny [6] evaluated the effect of keeping the refrigerator in a restricted or limited space, which caused inadequate heat transfer in the condenser, impacting the operation of the fridge. This space limitation can be attributed to user fault. In this sense, the inadequate load of food entered into the refrigerator also influences its thermal performance and energy consumption [7]; thus, the load can also be classified as a fault due to usage habits. Recently, Pardo-Cely et al. [8] proposed an experimental analysis to understand a refrigerator's thermal and energy behavior when mechanical or user's (usage habits) faults occur. The simulated faults were the fouling of the condenser surface, the variation in the speed of the fan attached to the condenser, and the lack of air circulation in the space where the compressor and condenser are located. The authors simulated different levels of fault, concluding that the refrigerator's energy consumption increased from 2% to 48%.

According to the above, the faults in a domestic refrigerator, whether mechanical or by the user, affect to a certain extent the fridge's thermal behavior and energy consumption. On the other hand, refrigerator designs in the home appliance market vary widely by each brand. Therefore, the present study proposes to expand the analysis of faults impact in refrigerators of different designs or volumetric capacities. Accordingly, we propose simulating and evaluating two faults: varying the fan's rotation speed coupled to the evaporator and restricting the surface area of the air returns inside the freezer in refrigerators of different volumetric capacities. The objective of the above is to quantify the fault in the thermal operation and energy consumption of both compartments of the refrigerators.

2. Test refrigerators

The experimental equipment used in this study is two domestic refrigerators with volumetric capacities and their respective design. Both refrigerators have two compartments, the freezer at the top and the fresh food compartment at the bottom, as shown in Figure 1. Refrigerator A is from the Daewoo brand and has a volumetric capacity of 0.3 m^3. It has two physically separated doors and an automatic defrosting system; it works with R134a refrigerant. Refrigerator B is a Mabe Sirius model with a volumetric capacity of 0.5 m^3 and uses R600a as a refrigerant. Both refrigerators are "No-frost" types, that is, they have an automatic defrost system, and cold air is distributed in both compartments through forced convection. Furthermore, the heat exchangers (evaporator and condenser) and the compressor have different designs. Table 1 shows the general characteristics of the main components of both refrigerators.



a) Refrigerator "A", Daewoo brand	b) Refrigerator "B", Mabe brand

Figure 1 Test refrigerators

Table 1 Characteristics of the main components of both refrigerators

	Refrigerator A	Refrigerator B
Compressor	Hermetic, RoHS brand model LU66XZ1, 60 Hz, 115 a 127 V, R134a	Hermetic, MCM Americas brand, 60 Hz,115 a 127 V, R600a
Condenser	Forced convection spiral tube type	Forced convection multilayer tube-wire type
Evaporator	U-arrangement with square fins	Spine finned U-type arrangement

2.1. Fault simulation

This study proposes the simulation of two common faults in domestic refrigeration equipment. The first is due to the continuous use of the fan attached to the evaporator. The second is due to usage habits such as obstruction of the air returns inside the freezer. Both faults are simulated to evaluate and quantify their effect on the thermal behavior within the compartments and the energy consumption of both refrigerators. Initially, the refrigerators are evaluated under ideal conditions as they leave the factory (the reference) for later comparison when the fault occurs in the refrigerator. The test suggests low, medium, and high levels of intensity to simulate the faults, thus modeling a gradual degradation of the fault. Each test is repeated twice for data reliability, so the results shown in Section 3 correspond to the averages.

2.1.1. Faults in refrigerator A

Fan. The refrigerator has an internal fan coupled to the evaporator to carry out forced convection distribution of the cold air flow in both compartments (see Figure 2), which can fail due to time of use or obstruction by food. This fan has an ORM-11119X2 motor whose average operating speed is 2200 rpm (as it leaves the factory). A change in the fan's rotation simulated the fault, obtaining a variation in the average voltage of the motor fan. A solid-state relay controlled through pulse width modulation (PWM) was conducted using Arduino. Thus, the pulse width uses a rotation range between 0 and 255, where 0 refers to the fan off, and 255 represents the fan working usually (as it leaves the factory). Therefore, we propose a pulse width of 237 for the low fault level; a pulse width of 219 for the medium level; and a pulse width of 200 for the high fault level. Because the fan's rotation speed concerning the PWM signal is not linear, the revolutions per minute were measured for each pulse width at the different proposed fault levels (see Table 1). Figure 2 shows the fan and relay coupling to simulate the fault in refrigerator A.

Figure 2 Refrigerator fan A and fault simulation

Air returns. The surface of the airflow returns inside the refrigerator, and it is usually blocked with food introduced day after day by the user. These returns located inside the freezer, at the bottom of the cover (see Figure 3), have a total length of 11.8 cm, distributed in three 3.3 cm-long slots with a separation of 1 cm between them. The slots are blocked with metal tape to simulate the fault. depending on the level of the fault. For this study, the obstruction indicating a low level of fault is defined by a blocked length of 2.75 cm, the middle-level obstruction by a length of 5.52 cm, and the high fault level obstruction by a blocked length of 8.28 cm.

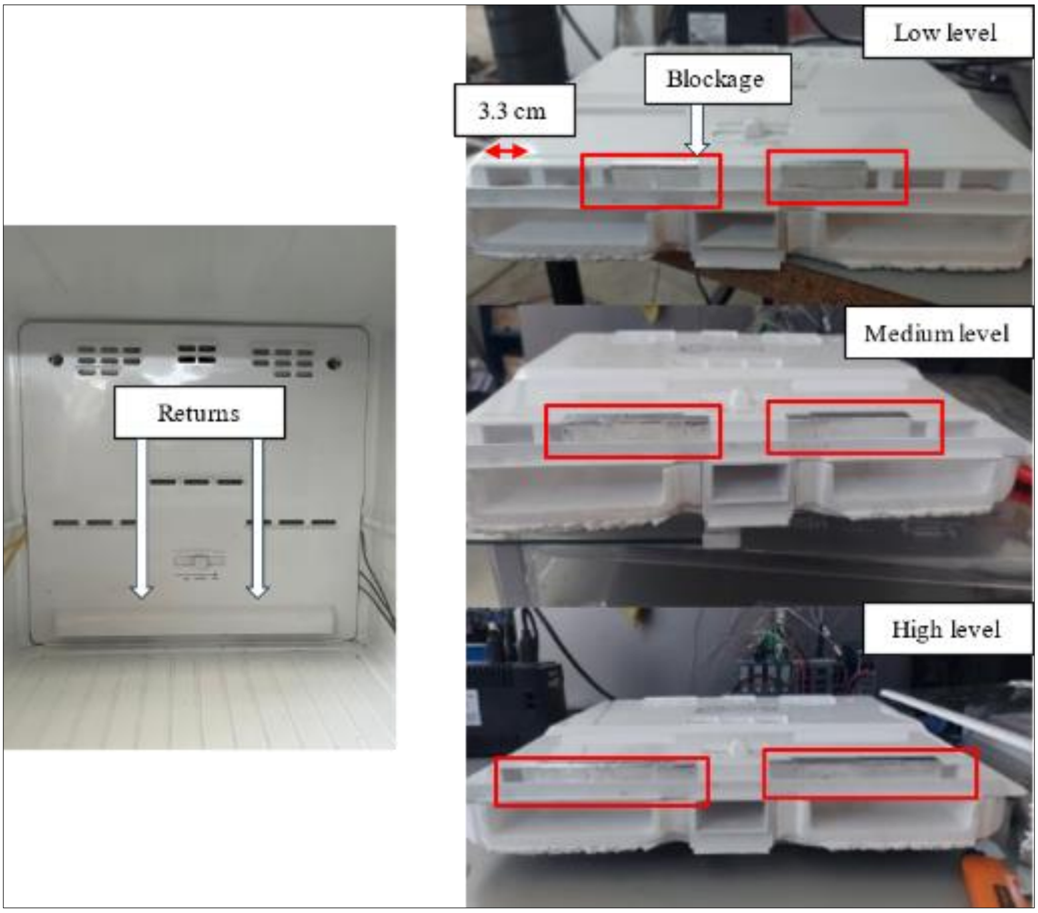


Figure 3 Refrigerator A returns and fault simulation

2.1.2. Faults in refrigerator B

Fan. Refrigerator B has a fan-motor model IS-23210MBE (see Figure 4), and its operating speed is 2500 rpm (from the factory). The fault induction is carried out in the fan motor by affecting the rotation speed, as was done for refrigerator A, where the speed is controlled by pulse width modulation generated with the Arduino software. The fault level depended on the pulse width. The low fault level was determined at 1600 rpm, the medium at 1400 rpm, and the high at 1200 rpm.

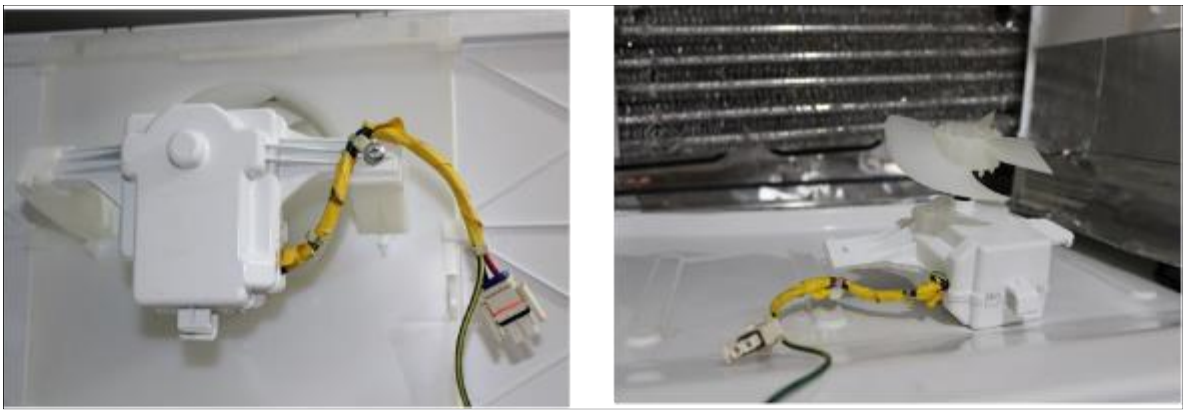


Figure 4 Refrigerator fan B and fault simulation

Air returns. Figure 5 illustrates the returns for refrigerator B. Note that its design is different from that of refrigerator A. The returns are located at the bottom of the freezer cover. The slots were blocked with metal tape to obtain a fault level. For this study, the low fault level was defined as an obstruction of 4.5 cm in length blocking the entire corresponding surface. For the medium level the obstruction was 9 cm in length, and for the high level, 12 cm.

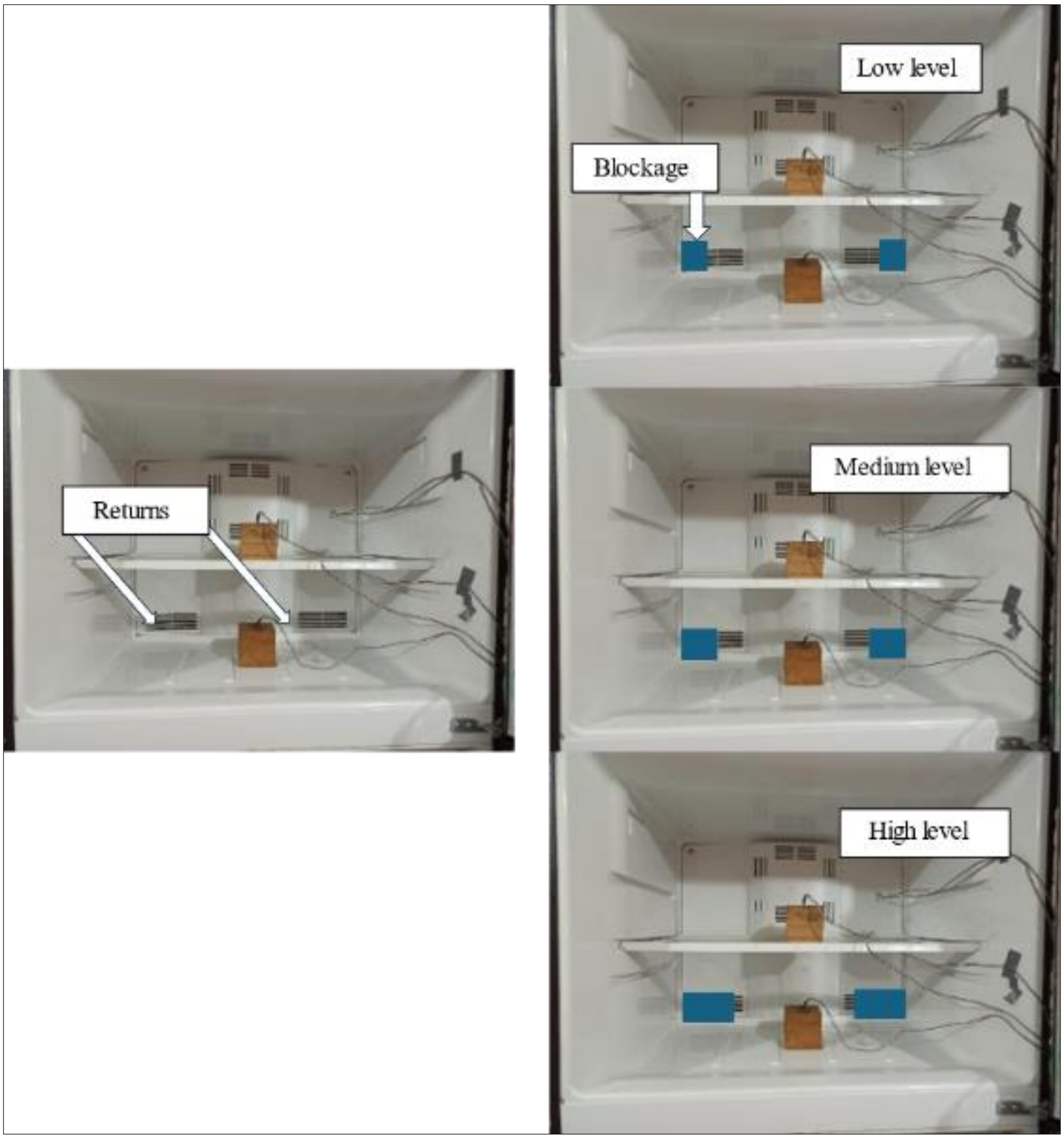


Figure 5 Refrigerator B returns and fault simulation

Table 2 summarizes the proposed fault levels for each refrigerator used in this study. In addition, the reference condition is indicated, that is, as they leave the factory (without faults). In the case of the simulated fan fault, the inadequate operation increases as the rotation speed decreases in both coolers. Regarding faults due to obstruction in the airflow returns, the fault level increases as the area for the return air passage decreases.

Table 2 Proposed fault levels for both refrigerators

			Fault levels		
	Fault	**Reference**	**Low**	**Medium**	**High**
Refrigerator A	Fan (RPM)	2200	2000	1800	1200
	Returns (cm)	Without obstruction	2.75	5.52	8.28
Refrigerator B	Fan (RPM)	2500	1600	1400	1200
	Returns (cm)	Without obstruction	4.5	9	12

2.2. Instrumentation and acquisition data

The refrigerators used in this work were instrumented to observe and analyze the thermal and energy behaviors during faults. For this purpose, five type J thermocouples (with a measurement sensitivity of 55μV/°C) were placed in both refrigerators. Two of which were located in the freezer and three in the fresh food compartment, distributed according to NOM-015-ENER-2018. Figure 6 shows the schematic location of the sensors. All tests were conducted behind closed doors in both compartments and in a space where the ambient temperature was recorded at 21 ± 1.5°C.

A National Instruments model NI-9213 card was used for temperature with an operating range of -40°C to +70°C. The module was connected to an NI cRIO-9030 chassis, a computer, and LabVIEW Signal Express software. The measurement of energy consumption was based on a Fluke 438-II energy analyzer (measurement accuracy ±3%). Data was gathered every 10 seconds for all tests, and each variable was to be measured in both refrigerators.

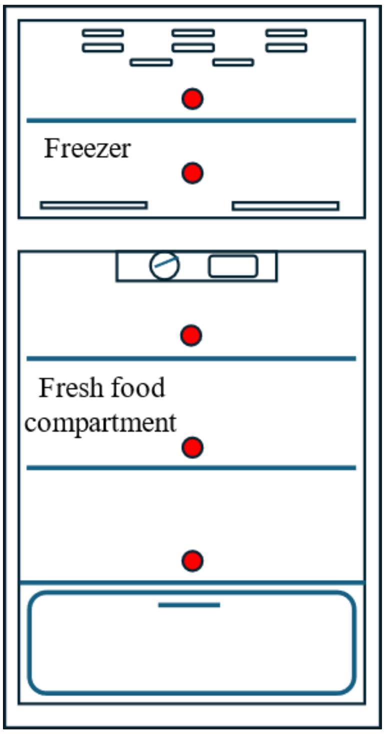


Figure 6 Location of the thermocouple within both compartments

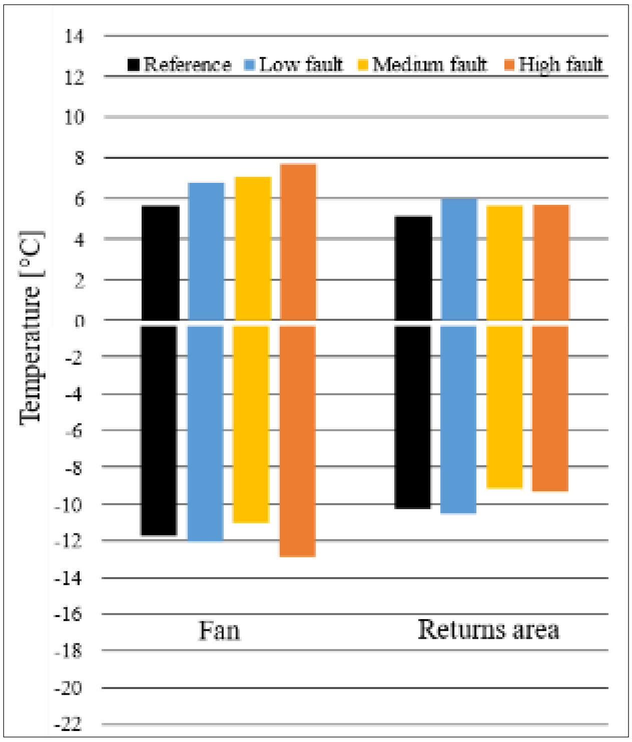
3. Results

The results in this section correspond to a direct comparison between refrigerators in terms of their thermal and energy performance for each simulated fault level. They show the behavior of the refrigerators in their reference condition (without faults) as well. The data shown corresponds to the average of two tests performed for each fault for data reliability.

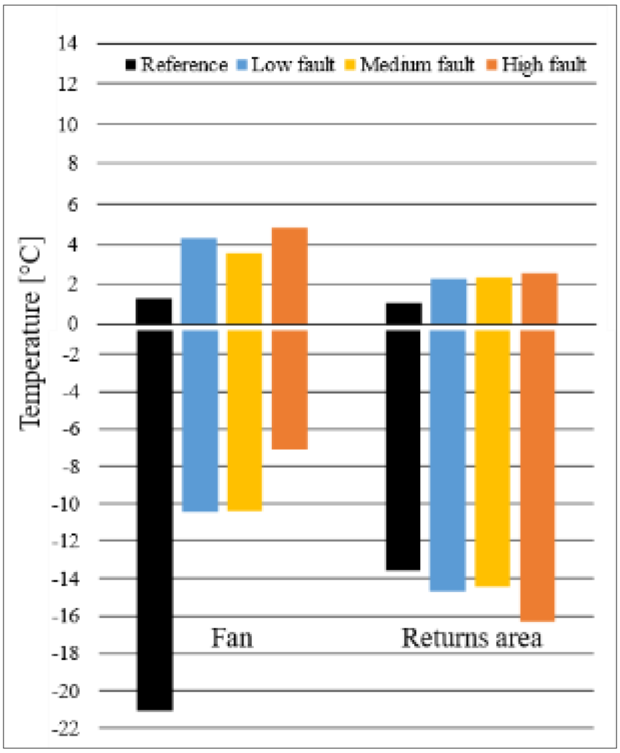
3.1. Thermal condition of the compartments

Figure 7 shows the thermal condition of the compartments of both refrigerators for the level of each simulated fault, fan, and return airflow through colors. The condition of the refrigerator is also shown in its reference state as it leaves the factory, which is indicated in black. It is worth mentioning that the reference test is performed for each simulated fault. For this reason, the results differ between each reference condition for the same refrigerator. A quick inspection shows that both faults cause heating in the fresh food compartments of both refrigerators. For example, a fan fault in refrigerator A causes temperature increases of up to 2°C at the high fault level compared to the baseline state. While for refrigerator B at the same level of fault, an increase of around 4 °C is obtained. This represents a more unfavorable impact for refrigerator B, which could impact the proper preservation of food. A more considerable thermal variation is also reflected in the freezer of refrigerator B, where the reference condition indicates -21 °C and the highest fan fault level reflects -7 °C, indicating a hot space unsuitable for products that require freezing conditions. There were no noticeable temperature changes regarding the fan's fault in the freezer of refrigerator A.

Regarding the fault in the area of the airflow returns, less thermal variation was observed in the compartments of refrigerator A and slightly more significant variation in the freezer of refrigerator B. Thermally, it can be concluded that a mechanical fault in the fan affects to a greater extent the fresh food compartment, the space where there is usually the most significant amount of food [7].



a) Refrigerator A



b) Refrigerator B

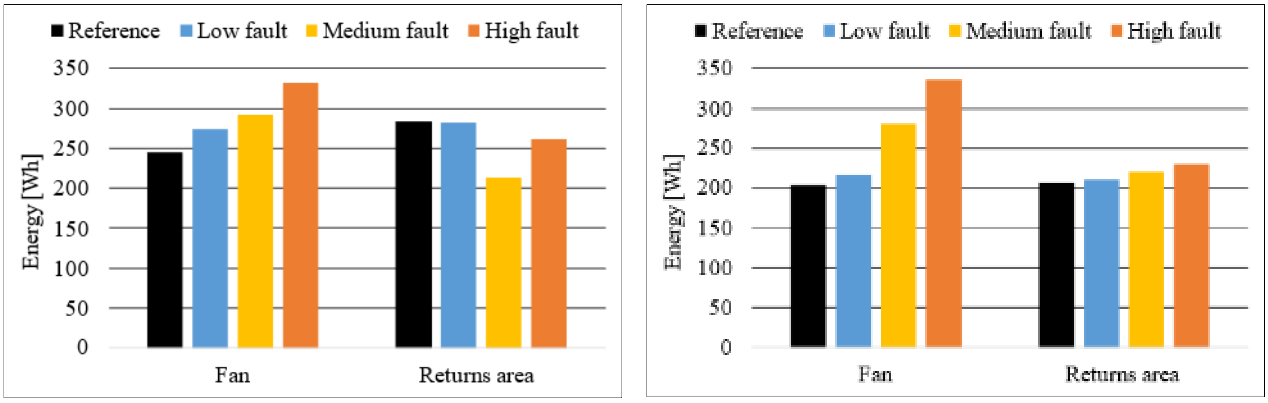
Figure 7 Thermal behavior of the compartments in both refrigerators

3.2. Energy consumption

Figure 8 shows the energy consumption of both refrigerators. It indicates the consumption that originates from each level of fault. Remember that the reference test was initially performed for each simulated fault. Energy consumption was measured for an approximate average of 4 hours for both refrigerators, during which time the refrigerator compartments are thermally stabilized. In the case of refrigerator A (Figure 8a) and the corresponding fan fault, the appliance consumes an average of 245 Wh for its reference condition (fault-free). As the fault level increases, a gradual increase is observed. The high level of fan fault causes an increase of approximately 88 Wh regarding the reference condition, representing 36%. Similar behavior for fan fault can be observed in refrigerator B (Figure 8b), where the high fault level causes an increase in power consumption of 65% (132 Wh) regarding the reference condition.

Regarding the fault obstructing the airflow returns area, refrigerator A presents variability in energy consumption; no defined behavior is observed. This may be due to the design of the refrigerator returns, which influences the thermal behavior, as shown in Figure 7a. Both compartments reflect a higher thermal condition than the reference condition, which indicates that the cooling periods of compressor work are shorter, indicating lower energy consumption.

In the case of refrigerator B, a slight increase in energy consumption can be observed as the fault level increases. Figure 7b shows that the thermal condition in the freezer of refrigerator B remains slightly lower than the refrigerator operating without fault, which would mean an increase in energy consumption.



a) Refrigerator A

b) Refrigerator B

Figure 8 Energy consumption in both refrigerators

According to the previous results, it can be concluded that faults have an impact on the thermal and energy performance of the refrigerator, whether due to mechanical aspects, such as in the case of the fan attached to the evaporator, or those attributed to the user due to improper use of the refrigerator, such as obstruction of the air returns. Our study confirms that, regardless of the type of refrigerator, the fault has a greater or lesser effect on the appliance's performance. Fan fault represents a more significant variation in energy consumption, so, from a design point of view, it would be an aspect that the manufacturer should take care of.

4. Conclusion

In the present study, the effect caused by faults on the thermal behavior of the compartments and energy consumption was evaluated in two refrigerators of different designs. The simulated faults correspond to the fan attached to the evaporator and the obstruction of the surface of the return airflow in the freezer. Three fault levels were proposed for the above, and the refrigerators were instrumented to measure temperature and energy consumption. Two tests were carried out for each fault level as well as for the reference condition, that is, the refrigerator as it leaves the factory without any faults. Among the relevant conclusions of the study, the following can be mentioned:

Overall, the fan's fault resulted in more unfavorable thermal conditions for food preservation, as warmer temperatures were obtained for both refrigerators in the fresh food compartment compared to those without faults. For example, refrigerator A showed a temperature increase of 2°C for the high fault level, while refrigerator B showed a 4°C increase. The design of refrigerator B showed the greatest thermal variation in the freezer as evidenced by an energy consumption of around 65% higher compared to the reference condition of the refrigerator.

As for the fault due to obstruction of the air return flow area, it affected to a lesser extent the thermal and energy performance of both refrigerators compared to the fan fault, with the design of refrigerator B the one showing the most notable changes in the performance behaviors.

Finally, this work emphasizes the importance of the design and useful life of accessories, such as the fan, as well as the usage habits for the proper operation of the appliance. Thus, a supervision or maintenance program by the user and recommendations for the suitable operation of refrigerators become essential.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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