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Thermal and Energy Evaluation of a Domestic Refrigerator under the Influence of the Thermal Load

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Received: 4 December 2018; Accepted: 22 January 2019; Published: 27 January 2019

Abstract: This study seeks to understand the thermal and energetic behavior of a domestic refrigerator more widely by experimentally evaluating the main effects of the thermal load (food) and the variation of the ambient temperature. To carry out the experiments, the thermal load was classified based on the results of a survey conducted on different consumers in the state of Guanajuato, Mexico. The thermal behavior of both compartments of the refrigerator, the total energy consumption, the power of the compressor in its first on-state, and the coefficient of performance, according to the classification of the thermal loads and the room temperature, were evaluated. Finally, it is verified that the thermal load and the room temperature have a significant influence on the energy performance of the refrigerator.

Keywords: energy consumption; thermal load; domestic refrigeration system

1. Introduction

The domestic refrigerator is one of the most popular household appliances because of its use in food preservation. Most of these refrigerators are based on vapor compression technology, and their continuous operation represents a high-energy consumption. Currently, it is claimed that the refrigeration sector (including air conditioning) consumes about 17% of the total electricity used worldwide, where there are currently more than 1.5 billion domestic refrigerators in use [1].

In Mexico, approximately 86% of households have at least one refrigerator, representing more than 28 million domestic refrigerators in use [2]. According to the Trust for Saving Electrical Energy (FIDE, from its Spanish initials), the refrigerator represents around 30% of the total energy consumption in a household [3]. For several decades, there was an imminent growth in the refrigeration industry, which also led to a considerable increase in energy consumption. Thus, these appliances are a point of interest in search of energy improvements. Some methods, such as energy labeling, take into account the efficiency of the product [4], which guarantees to some extent the regulations on energy saving. Thus, the labeling provides a guide to study different mechanisms that can increase a refrigerator's energy efficiency, such as the design of the main components, thermal insulation, adequate thermal behavior, and use of alternative refrigerants, among others [5]. However, the refrigerators' energy consumption does not only depend on the technical characteristics of the components, but it also depends on the usage habits of the consumer and the environmental conditions where the appliance is located, as it is specified on the energy label [6].

There are factors such as ambient or room temperature [7], relative humidity [8], and frost formation, [9], among others, that significantly affect the energy performance of a domestic refrigerator.

In addition to the above, other factors depend on the usage habits of the consumer [10], who plays a significant role in the cold chain and the proper conservation of food. Among these factors, the following can be mentioned: the frequency in the opening of doors, the position of the thermostat, the amount of food, and the cleaning in the case of external condensers, among others.

In the literature, there are works on the study of these factors; for instance, Saidur et al. [11] experimentally evaluated the temperature of the room and other factors, such as the opening of doors and the position of the thermostat, on the energy consumption of a refrigerator. The authors concluded that the temperature of the room affects, to a greater extent, the energy consumption, followed by the opening of doors. Hasanuzzaman et al. [12] analyzed the energy consumption of a domestic refrigerator by varying factors such as the number of door openings, opening duration, cabinet load, thermostat position, and room temperature. The authors found that all factors influence energy consumption, with the most notorious case (with a 40% increase) when the refrigerator operates with open doors compared to when it is used with closed doors. Later, the authors extended their study to analyze factors such as the position of the thermostat, the thermal load, and the ambient temperature on the heat transfer and the energy consumption of the refrigerator. The authors concluded that the largest contributions occurred when the thermal load varied from 0 to 12 kg, with an increase in energy consumption of 58%, and when the ambient temperature changed from 18 °C to 30 °C, with a 41% increase [13]. Khan et al. [14] presented another work, similar to the previous studies, confirming an increase in energy consumption of up to 30% depending on the frequency of door opening, an increase of 30% when the ambient temperature varied from 20 °C to 30 °C, and an increase of 59% when the load varied from 0 m^3 to 0.007 m^3.

In the literature, there are also works with a statistical approach based on a series of surveys and related to the usage habits of consumers. For instance, Janjic et al. [15] investigated the conditions, such as temperature, cleanliness, and storage practices, under which food is subjected inside refrigerators. The authors reported that about half of the refrigerators considered in the survey had an incorrect food storage practice. Furthermore, the internal temperature of the refrigerator was considered to be high compared to the recommended temperature for this household appliance. Geppert and Stammiger [16] evaluated the behavior of the consumer in relation to the use of the refrigerator and the main characteristics of these appliances. They analyzed the conditions of the ambient temperature, the internal temperature of the compartment, and the heat sources near the refrigerator, aspects that influence the thermal and energetic performance of the household appliance. Based on the results, the authors made a series of recommendations on energy efficiency, and concluded that there is a lack of information provided to the consumers on this subject. Later, the authors extended their study to experimentally evaluate some of the operational factors that reflect the daily use of refrigerators such as the ambient temperature, the position of the thermostat, and the thermal load influenced by the amount of food. They concluded that the energy consumption is very sensitive to the ambient temperature and, to a lesser extent, the internal temperature of the refrigerator and the thermal load [17]. On the other hand, James et al. [18] made a review of diverse works where they analyzed factors such as the frequency in the opening of doors, the cleaning, the handling and storage of food, and the age of the refrigerator. This compilation was carried out aiming to analyze the thermal behavior of the refrigerator and the cleaning of the food on the impact on the consumers' health. Thus, it is clear that factors, where the consumer is involved, reflect in a meaningful way the energetic and thermal behavior of the refrigerator, together with the environmental conditions where the appliance is located.

The literature review indicates the importance of external factors on the energy consumption of domestic refrigerators, and it also shows that those factors are unrelated to the design of the refrigerator components. One of the factors that affects the energy consumption to a great extent is the room temperature where the appliance is located. Other factors of importance in the energetic operation of the refrigerator are also those related to the usage habits of the consumer. On the other hand, in the studies found in the literature, there is no justification for the thermal load (food) evaluated.

In addition, the results presented with variation in thermal load focus only on the energy performance of the refrigerator.

In this paper, with knowledge based on surveys on usage habits, the energy consumption and the average temperature in both compartments of a domestic refrigerator are evaluated when the thermal load (food) is varied. Moreover, the effect of room temperature on refrigerator performance is analyzed, with both factors (thermal load and temperature) recorded in the surveys. Thus, this paper provides a basis for a deeper analysis and a better understanding of the energy consumption of a refrigerator. This type of study should facilitate recommendations through the manufacturer, from an energy and thermal viewpoint, on how to better use the appliance based on the amount of food and, in general, on the habits of use that cause great increases in energy consumption and which can degrade food quality due to inappropriate temperatures in the compartments. As an additional contribution, this study provides information to consumers and manufacturers as a reinforcement to understand how refrigerator usage habits affect thermal conditions and energy consumption and, thus, improve the refrigerator use recommendations.

The rest of the paper is organized as follows: in Section 2, the thermal load obtained from surveys is shown. In Section 3, the experimental refrigerator and the tests performed are presented. Section 4 shows the main results of thermal behavior of compartments and energy consumption of the refrigerator. Finally, Section 5 summarizes the main conclusion of the study.

2. Presence of Thermal Load

Among the different factors influencing the proper performance of a domestic refrigerator, the adequate distribution of airflow in the compartments is highlighted, which has an impact on thermal behavior and, in turn, affects energy consumption. In this respect, the thermal load (food stored in the refrigerator's compartments) also influences the thermal behavior, where the consumer plays a key role in the use of this appliance.

The thermal loads experimentally evaluated in this work are based on the records of surveys applied to 200 random consumers in Salamanca, Guanajuato, Mexico. Along with the questions asked to analyze the use of the refrigerator regarding the thermal load, and with previous consent of the respondents, visual evidence was collected, as well as the measurement of the amount of food stored in the fresh-food compartments (crisper drawers) and in the freezer. Figure 1 shows the conditions of thermal load in both compartments, for which the filling of the refrigerator was classified in four ranges, as shown in the figure. The light-blue color corresponds to the thermal load in the food compartment, whereas the dark-blue color represents the amount of food in the freezer.

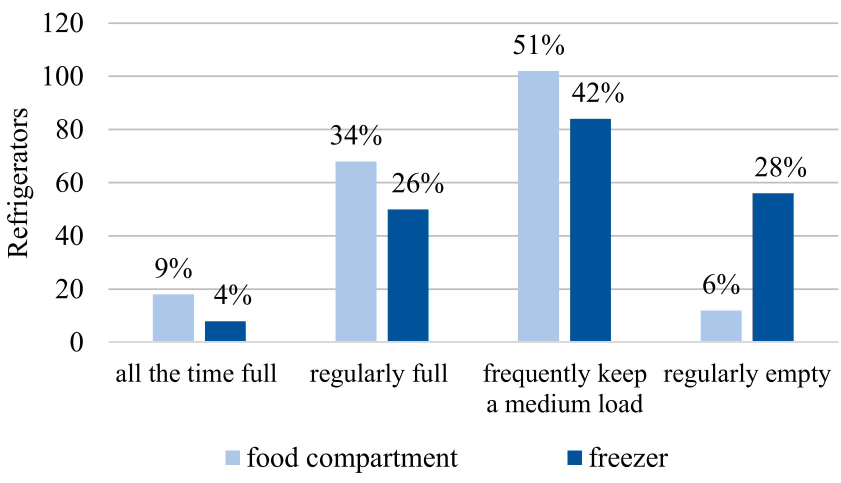


Figure 1. Distribution of thermal load in the refrigerator.

The higher percentages correspond to the consumers frequently keeping their refrigerator at a medium load—51% of consumers (102 refrigerators) for the food compartment and 42% (84 refrigerators) for the freezer. On the other hand, a low percentage of consumers keep their refrigerator full all the time—9% for the food compartment and 4% for the freezer. According to the statistic shown in Figure 1, an average of eight thermal loads were defined in this work (see Table 2). Moreover, during the surveys, the temperature of the room where the refrigerator was located was also measured; this way, an average temperature sample was set during some experimental tests to analyze their effect on the refrigerator's performance.

3. Experimental Refrigerator

According to the surveys, it was observed that a great percentage of consumers have medium-sized refrigerators at home (two-doors and no-frost type). For this reason, a refrigerator meeting most of the features of the survey's refrigerators was used, as shown in Figure 2. The two-door experimental refrigerator had a volume capacity of 0.3 m^3 (300 L), separating the fresh-food compartment at the bottom and the frozen-food compartment at the top. The refrigerator was a no-frost type and the heat transfer in the freezer occurred via forced convection. Table 1 shows more general features of the experimental refrigerator.

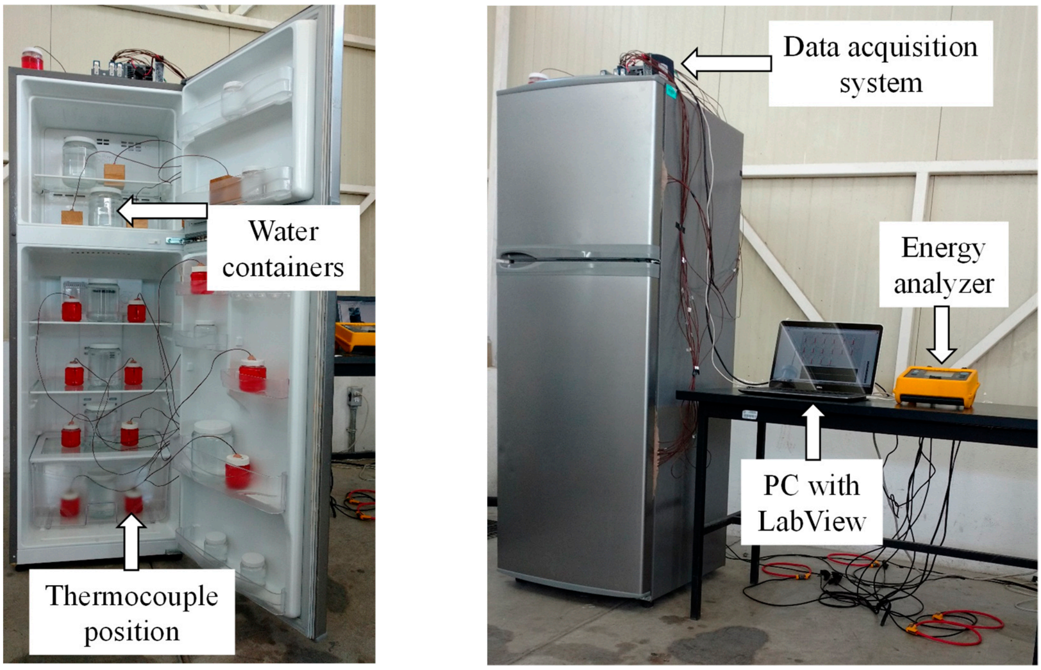
Table 1. General features of the experimental refrigerator.

External Dimensions	
Width	0.54 m
Length	0.67 m
Height	1.64 m
Net weight	52.4 kg
System Characteristics	
Refrigeration	Forced convection
Melting element	By electrical resistance
Defrost	Automatic
Refrigerant	R134a
Voltage/Current	127~/60 Hz/1.1 A

3.1. Instrumentation and Measurements

The refrigerator was used in this research to evaluate the thermal behavior of the compartments, as well as the energy consumption when the thermal load varied in both compartments according to the surveys. To measure the temperature, 15 J-type thermocouples were used with an uncertainty of measurement of ±0.3 K. Eleven thermocouples were distributed in the food compartment and were located within containers of 0.245 L with a mixture of 50% water and 50% glycol. Four thermocouples were placed in the freezer inside wooden cubes, due to their high capacity of humidity absorption, thus allowing a constant measurement of the temperature. In Figure 2a, the distribution of the thermocouples in both compartments is illustrated; moreover, the distribution of the water compartments can be seen, simulating the thermal load for a specific case. On the other hand, to measure the energy consumption, a Fluke 1735 energy logger (Fluke, Everett, WA, USA) calibrated with a measurement error of ±1.5% was utilized.

The thermocouples were connected to an NI-9213 card attached to the chassis NI cRIO-9030 (National Instruments (NI), Austin, TX, USA). Via a Universal Serial Bus (USB) connection to a computer, a real-time visualization was possible with the SignalExpress software (National Instruments (NI), Austin, TX, USA) programmed in LabView. The temperature measurement was recorded in intervals of 10 seconds, whereas the measurement of the energy consumption was set in intervals of one minute; the data were stored on a Secure Digital (SD) card. Both the temperature and energy consumption measurements were done simultaneously.



(**a**) (**b**)

Figure 2. Experimental test bench: (**a**) temperature distribution; (**b**) instrumentation.

3.2. Proposed Tests

As mentioned before, the aim of this study was to evaluate the effect of the thermal load (food) on the thermal and energy behavior of a domestic refrigerator. In this sense, the foods were simulated with containers full of water and whose volume capacities were 0.3, 1, 1.8, and 4 L.

According to the information gathered in the surveys, different ranges of thermal load were classified (see Figure 1), where the total variation of the average thermal load (food compartment and freezer) went from a minimal load of 7 kg (Regularly empty, 5 kg in the fresh-food compartment and 2 kg in the freezer) to a maximum load of 39 kg (All the time full, 27 kg in the fresh-food compartment and 12 kg in the freezer). Additionally, ambient temperatures of 20 °C and 25 °C, with a variation in intervals of ±0.5 °C, were frequently measured in the room (giving to surveys) where the refrigerator was located and, in relation to these ambient temperatures, the loads were also grouped. The above data can be observed in Table 2, where a reference condition is included, that is, when the refrigerator remains empty.

Table 2. Thermal loads in both compartments under two conditions of room temperature.

Room Temperature	**20 °C**		**25 °C**	
Thermal Load	**Fresh-Food Compartment (kg)**	**Freezer (kg)**	**Fresh-Food Compartment (kg)**	**Freezer (kg)**
Reference	0	0	0	0
Regularly empty	5	2	11	2
Frequently keep at medium load	27	2	18	2
Regularly full	27	5	18	7
All the time full	27	7	27	12

All the tests were performed in the same way. Firstly, the refrigerator was loaded with a certain amount of food, as shown in Table 2. Once the refrigerator was loaded, the test initiated with the start-up of the refrigerator and at the corresponding room temperature of the load, according to Table 2. Note that, for each test, the refrigerator and the thermal load were at room temperature. The test continued until the thermal stability was reached in both compartments and, during the test, the doors of the refrigerator were kept closed. Also, the damper (control element) remained in the fifth position, exactly as it was when the refrigerator left the factory. After finishing the test, the refrigerator was unplugged and defrosted so that the refrigerator could reach room temperature.

4. Results and Discussion

In this section, the main results coming from the thermal behavior of both compartments of the refrigerator are presented, as well as the energy consumption for different conditions of the thermal load and room temperature. Each test was done in triplicate, aiming to yield greater reliability in the results, which reflect the average of the temperature and energy measurements. Moreover, the presented results are those obtained when the thermal stability was achieved in both compartments.

4.1. Effect of Thermal Load on Thermal Behavior of the Compartments

Figure 3 shows the conditions of temperature in both compartments of the refrigerator for a room temperature of 20 ± 1 °C. The compartment temperature represents the average of the thermocouples placed within them. The horizontal axis of the figure represents the thermal loads, where 0 kg corresponds to an empty refrigerator (without thermal load) in both compartments, and 7, 29, 32, and 34 kg correspond statistically to the average load (fresh-food compartment and freezer) of each of the classifications of the thermal load shown in Figure 1 and Table 2. The light-blue color represents the temperature of the food compartment, and the dark-blue color represents the temperature of the freezer. In Figure 3, it is observed that the temperature of the food compartment showed relatively small changes as the thermal load increased, remaining at a maximum difference of 2 °C between loads 7 and 29 kg. Furthermore, the freezer experienced a maximum thermal variability of 4 °C between the loads of 7 and 29 kg.

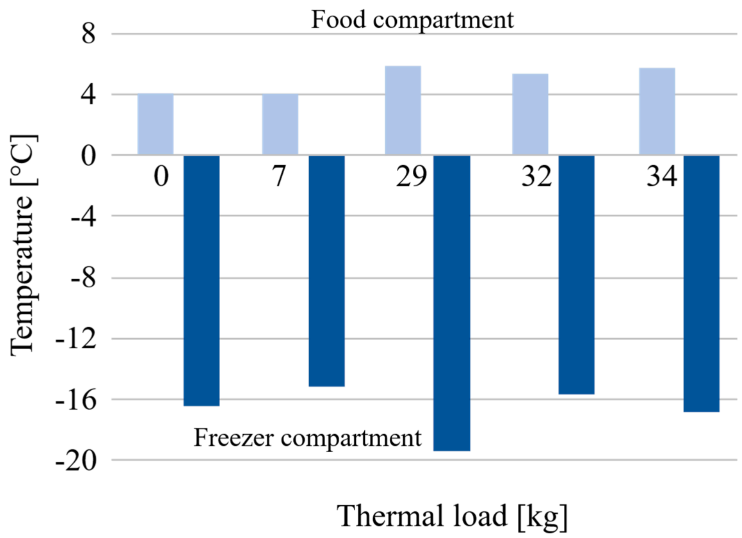


Figure 3. Thermal behavior of the compartments at 20 °C.

On the other hand, in Figure 4, the thermal behavior of both compartments at different thermal loads and at a room temperature of 25 ± 1 °C is illustrated. It is worth mentioning that these thermal loads are the most representative for the room temperature measured in the surveys. It can be observed in the figure that both compartments represented a variable thermal condition, without having a clear correspondence between the thermal load and the compartment temperature. The maximum temperature variation in the food compartment was 2.2 °C (0 and 20 kg), while, in the freezer, it was 2.7 °C (0 and 25 kg).

Consistent with these behaviors, it can be confirmed that the refrigerator is capable enough to maintain an operational range of adequate temperatures in both compartments, regardless of the amount of thermal load.

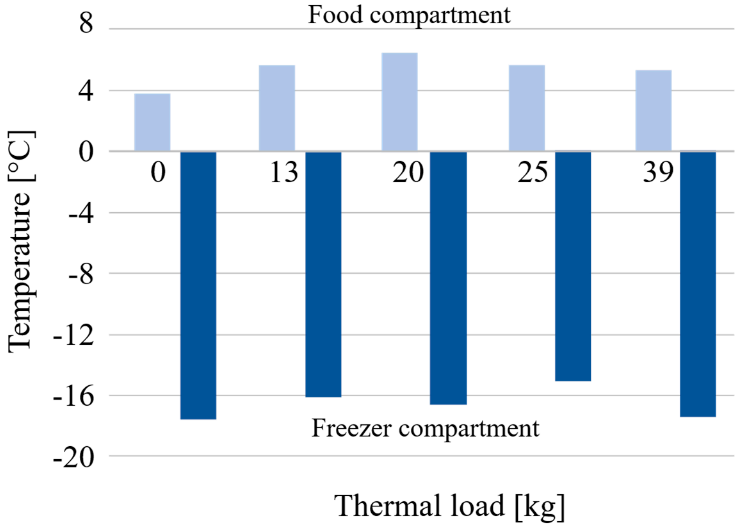


Figure 4. Thermal behavior of the compartments at 25 °C.

4.2. Effect of Thermal Load on Energy Consumption

The cooling capacity of a refrigerator is directly proportional to the cabinet inner thermal load (mass), which depends on the food initial temperature, the cabinet temperature, the specific heat, and the latent heat of the thermal load (water). Moreover, this mass is heated during the off-state of the compressor for cooling again during the on-state. Therefore, the energy consumption must increase as the thermal load in the refrigerator increases. In this sense, Figure 5 shows the total energy consumed by the refrigerator for the different thermal loads. Moreover, the energy behavior is shown for two conditions of room temperature. It can be clearly observed that, when the thermal load increased, the energy consumption also increased; these are similar behaviors found by References [12,14]. In Figure 5, it can be noticed that the magnitude of energy behavior at a temperature of 25 °C was higher than at a room temperature of 20 °C. Here, it is clear that the increase in room temperature caused an increase in the thermal leap between the ambient and the cabinet; thus, a significant amount of heat was transferred via conduction through the refrigerator's walls. For example, in Figure 5 it can be observed that, for the reference load (0 kg), there was an increase of 0.4 kWh for a temperature condition ranging from 20 °C to 25 °C; on the other hand, for the ambient condition of 20 °C, there was an increase ranging from 0.4 kWh (0 kg) to 3.5 kWh (34 kg); this values ranged from 0.8 kWh (0 kg) to 4.5 kWh (39 kg) for the temperature of 25 °C. Note that these energy consumptions vary in accordance with the thermal stabilization time of each test (see Table 3). Based on Figure 5, it was concluded that the thermal load represents a strong influence on the refrigerator's energy consumption. Finally, it can be said that, as the thermal load increases, so does the evaporation temperature. Therefore, the refrigeration cycle responds according to the evaporation temperature.

In Table 3, more information about the refrigerator's energy behavior is provided. It can be noted that, for the reference test (0 kg), the time estimated to reach thermal stability increased around 4 h for a condition of ambient temperature (room temperature) fluctuating from 20 °C to 25 °C. This increase caused the switch-on (on-state) percentage of the compressor to rise to 4%, which represents an increase of 0.029 kWh per operating hour. On/off cycles of the compressor clearly evidence the thermal behavior of the refrigerator compartments, which is linked to the temperature control in relation to the position of the damper. It is, therefore, consistent that the time of thermal stability increases as the thermal load increases and due to the increase in ambient temperature. With regard the work cycles shown in the table, a correlation referring to the load increase does not exist. Note that the percentage switch-on and the cycles decreased as the thermal load increased (e.g., from 29 to 32 kg (20 °C) and from 20 to 25 kg (25 °C)). For these conditions, the thermal load of the food compartment remained constant, while the freezer load increased in each test (see Table 2). Note that, for this particular refrigerator, the compressor regulation work is linked to the temperature of the food compartment and to the temperature of the freezer.

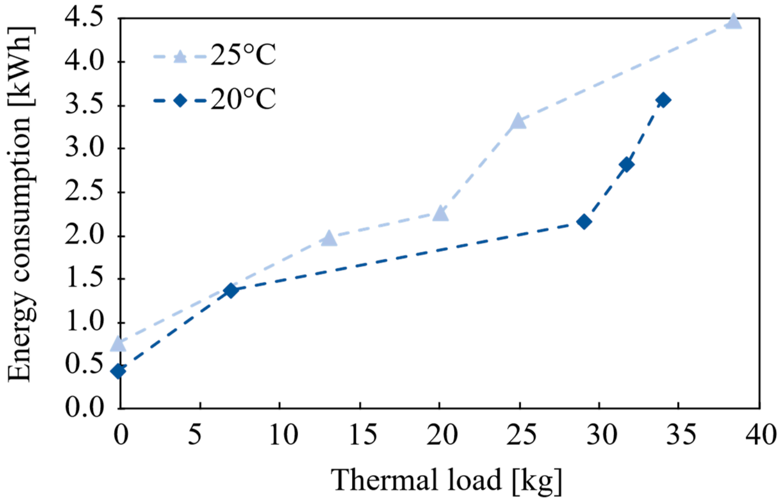


Figure 5. Energy consumption for different thermal loads.

Table 3. Energy behavior at different loads and constant ambient temperature.

Room Temperature (°C)	Thermal Load (kg)	Thermal Stability Time (h)	% Switch-On	Total Energy (kWh)	Cycles (24 h)
20	0	8	32	0.4	24
	7	21	35	1.4	21
	29	24	40	2.2	27
	32	33	37	2.8	24
	34	38	38	3.6	25
25	0	12	36	0.8	24
	13	25	39	2.0	34
	20	25	42	2.3	34
	25	38	37	3.3	26
	39	46	36	4.5	24

4.3. Effect of Thermal Load on the First On-State of the Compressor

The stage consuming the most energy in a household refrigerator originated when the foods were stored for their cooling. Therefore, it is recommended that this process be quick to avoid inappropriate conservation. For this reason, the first on-state of the compressor when the refrigerator is started is larger than the following ones. This occurs when the refrigerator contains too much thermal load (food), as shown in Figure 6. The figure shows the power of the compressor for the different thermal loads mentioned above. Figure 6a corresponds to a room temperature of 20 °C, and Figure 6b corresponds to a temperature of 25 °C. In both figures, it is clearly evident that the power input of the first on-state was linked to the amount of food stored in the refrigerator. Some studies mentioned that the additional energy consumption originated during the food-cooling stage [17]. This cooling stage is particularly evident during the first on-state of the compressor. In both figures, at the beginning of each cycle, there was a high-power peak due to the normal behavior of the electric motor. In addition, an increase in power was observed as the load increased; this conditions the on/off cycles of the compressor, requiring greater power to lower the temperature for a greater quantity of food.

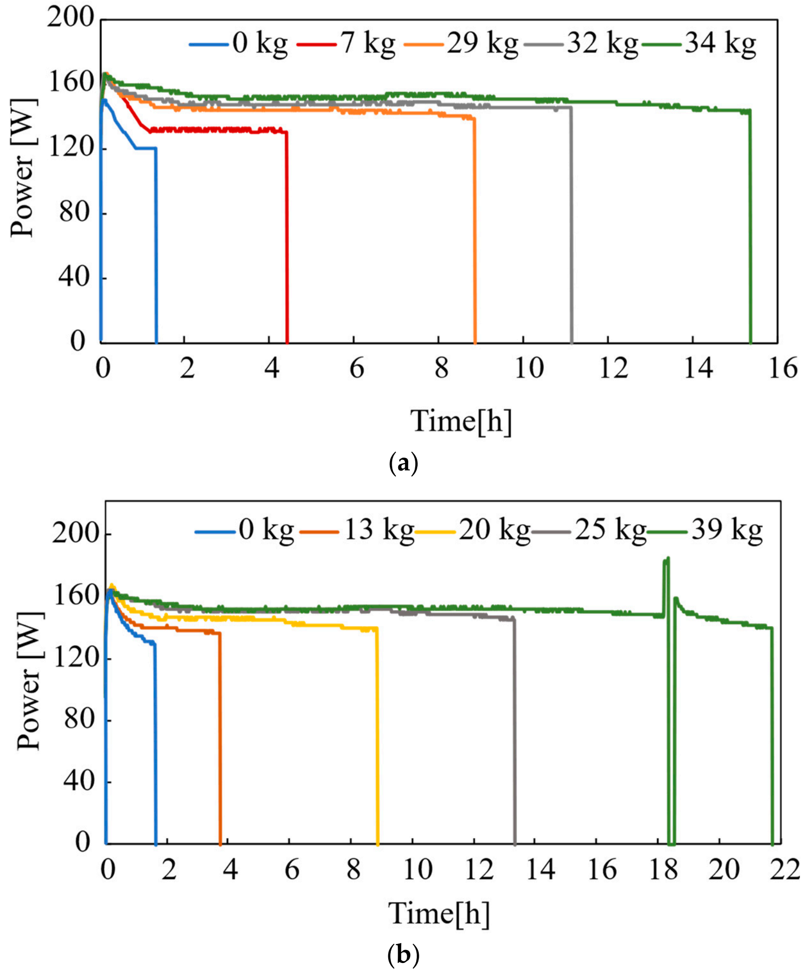


Figure 6. Power during the first on-state of the compressor: (**a**) room temperature at 20 °C; (**b**) room temperature at 25 °C.

As mentioned before, the ambient temperature affects the refrigerator's energy behavior to a large extent, as can be seen in Figure 6a,b. For the specific case of the reference load (0 kg), there was a difference in the average of the power of approximately 11 W, which indicates a power increase when the room or ambient temperature increased by 5 °C. This reflects an increase of 0.05 kWh in energy consumption. Thus, it is well known that the domestic refrigerator's electricity consumption is very sensitive to the ambient temperature [11]. Another aspect to observe in Figure 6b is that the thermal load of 39 kg represented the condition that consumed the most energy and whose on-time of the compressor was approximately 21 h. Moreover, in this case, it can be noticed that, at around 18 hours, a defrost occurred, indicated by the power increase, which in turn caused the compressor to shut down. Finally, it can be concluded that the on-time of the compressor on the first start increased when the thermal load increased; this behavior was reflected in the total energy consumption of the refrigerator.

4.4. Effect of Ambient Temperature on Thermal Behavior of the Compartments with a Constant Thermal Load

In order to expand this study based on survey data, in Figure 7, the average temperature of the food compartment for a constant thermal load and under two different conditions of room temperature is illustrated. The fading of the gray color in the bars represents a condition of low room temperature, whereas the discoloration of the blue color represents a higher room temperature. In Figure 7, it can be observed that, for a certain load, an increase in the room temperature caused a rise in the temperature of the fresh-food compartment (FF). For example, for the load of 13 kg, the increase from 16 to 25 °C in room temperature caused an increase of approximately 1.5 °C in the food compartment. Note that the foregoing is based on the thermal stability in the food compartment and for a fixed condition of the damper set at 5. For the thermal loads of 20 and 23 kg, a very similar thermal behavior existed, where the average temperature of the compartment experienced an increase for both room temperatures, showing an average thermal difference of 0.6 °C in both cases. Finally, for the thermal load of 30 kg, it can be noted that the average temperature reached in the food compartment for both room conditions was almost the same, around 6 °C.

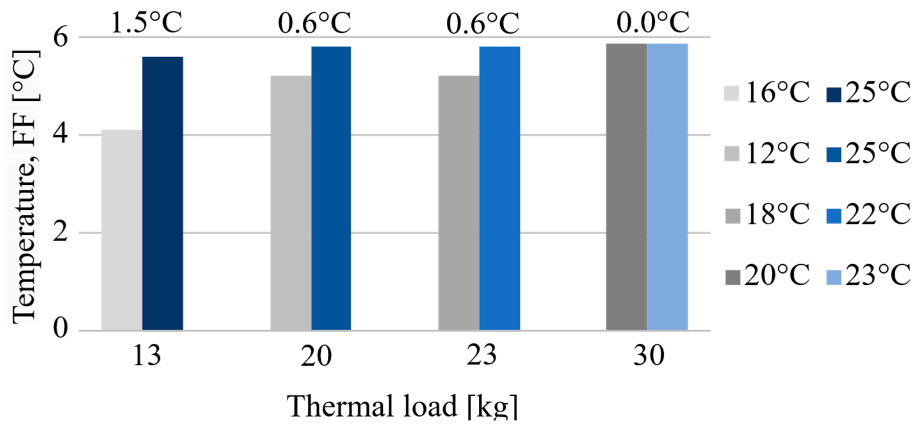


Figure 7. Temperature in the fresh-food compartment maintaining the constant thermal load at two ambient temperature conditions.

With respect to the average thermal behavior of the freezer (FZ), Figure 8 shows the ambient temperature effect for constant thermal loads. It can be seen that, when a constant thermal load was subjected to two room temperatures, the lowest average freezer temperature corresponded to the highest room temperature condition. For example, for the loads of 13, 20, and 23 kg, a difference in the temperature of 2, 2.3, and 2.6 °C, respectively, was obtained in this compartment, observing the effect of the room temperature rise. For the load of 30 kg, as also seen in Figure 7, the thermal difference was practically very small (about 0.6 °C).

Based on the reported results in this section and in the previous sections, it can be said that, for different thermal loads and different ambient temperatures, the refrigerator has the capacity to maintain an adequate thermal behavior for food preservation. However, this is achieved with a variation in energy consumption according to the ambient condition and the habit of use in the thermal load management.

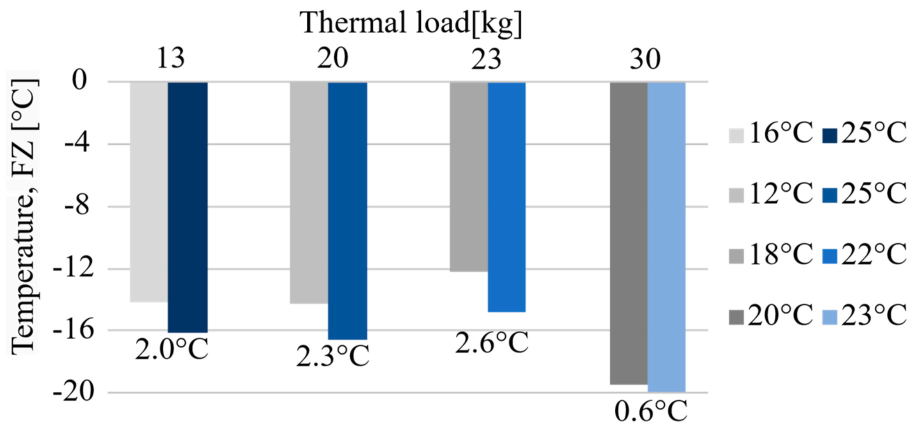


Figure 8. Temperature in the freezer compartment maintaining a constant thermal load at two temperature conditions.

4.5. Effect of Ambient Temperature on Energy Consumption with a Constant Thermal Load

Figure 9 shows the energy consumption when the refrigerator worked with constant thermal loads and at two room temperature conditions. The fading in gray and blue colors indicates the room temperatures. The energy increase percentage for each thermal load subjected to two conditions of ambient temperature is indicated at the top of the bars. It can be clearly observed that the increase of the ambient temperature caused an increase in energy consumption. For example, the load of 20 kg represented a greater increase in energy consumption, around 72% for an ambient thermal difference of 13 °C (room temperature between 12 °C and 25 °C). For this increase in the ambient temperature, the energy consumption of the refrigerator varied from 1.3 kWh/day to 2.3 kWh/day, a rise of 73 Wh/day per °C.

In the literature, there are works that reported information about the energy consumption for refrigerators of volumetric capacity different from the one evaluated in this work. The range of thermal load was also different. In order to show the results and compare the orders of magnitude, Hasanuzzaman et al. [12] experimentally concluded that, when the ambient temperature experienced an increase of 12 °C, the energy consumption varied from 2.13 kW/day to 3.64 kW/day, increasing around 126 Wh/day per °C rise in the ambient temperature of a 460-L refrigerator. Masjuki et al. [8] found that, when the ambient temperature increased 15 °C (from 16 to 31 °C), the energy consumption increased from 0.56 kWh/day to 1.12 kWh/day, representing an energy consumption around 40 Wh/day per °C rise in the ambient temperature for a 150-L refrigerator. Meier [19] concluded that in an increase in the ambient temperature of 11 °C (from 17 °C to 28 °C), the energy consumption varied from 1.25 kWh to 2.6 kWh/day. Finally, based on Figure 9, it was concluded that there is a strong influence of the ambient or room temperature on the domestic refrigerator's energy consumption.

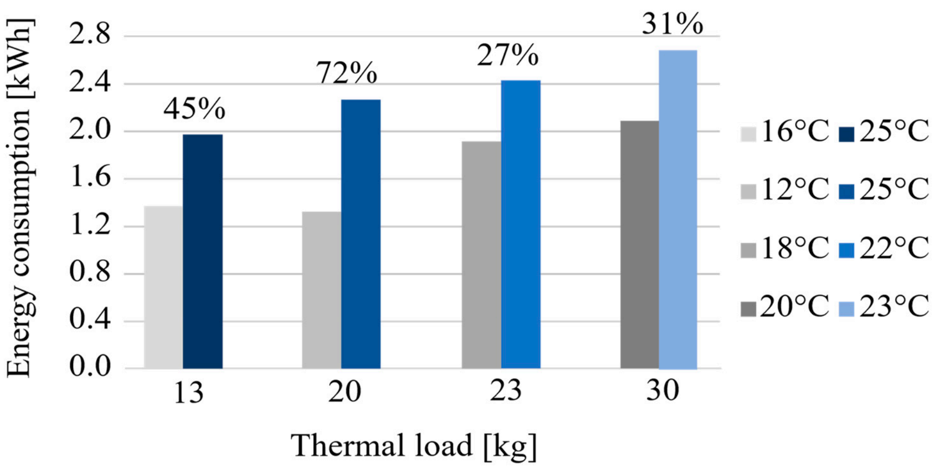


Figure 9. Energy consumption at different conditions of ambient temperature.

On the other hand, the quantity of heat to be removed can be estimated from knowledge of the thermal load (water), including its initial state at the entrance of the compartments, final state, mass, specific heat above and below freezing temperature, and latent heat [8]. Thus, the coefficient of performance (*COP*) can be calculated as follows for heat removed from the food compartment:

$$Q_{FF} = m_{FF} Cp_{water} (T_{amb} - T_{FF}). \tag{1}$$

That for heat removed from the freezer can be calculated as follows:

$$Q_{FZ} = Q_{FZ_1} + Q_{FZ_2} + Q_{FZ_3}; \tag{2}$$

$$Q_{FZ_1} = m_{FZ} Cp_{water} (T_{amb} - 0°C); \tag{3}$$

$$Q_{FZ_2} = m_{FZ}h_f; \quad (4)$$

$$Q_{FZ_3} = m_{FZ}Cp_{frost}(0^\circ C - T_{FZ}). \quad (5)$$

The capacity of the refrigeration system for the thermal load can be determined from the time set aside for heat removal:

$$CC = \frac{Q_{FF} + Q_{FZ}}{3600\ t}. \quad (6)$$

Therefore, the *COP* can be estimated as

$$COP = \frac{CC}{E/t}. \quad (7)$$

Figure 10 illustrates the behavior of the coefficient of performance (*COP*) of the domestic refrigerator under study. It can be seen that, for a constant load, there was a decrease in *COP* as the room temperature increased. For example, for a thermal load of 13 kg, there was a decrease in *COP* of 10% when going from 16 °C to 25 °C. An increase in room temperature reduced the overall refrigeration system *COP* by increasing the difference between the evaporating and condensing temperature.

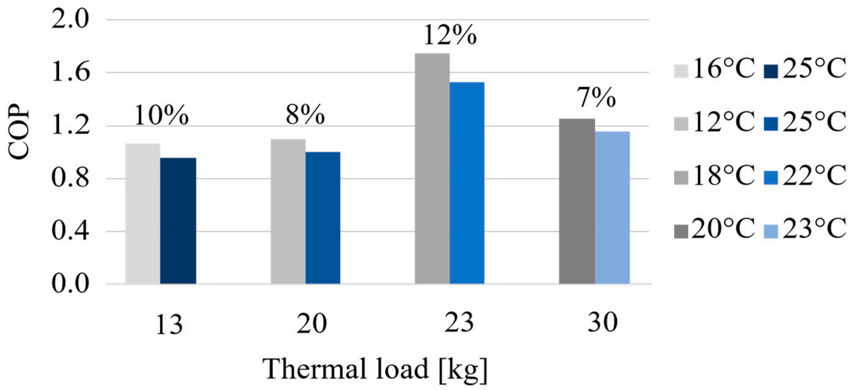


Figure 10. Coefficient of performance at different conditions of ambient temperature.

Table 4 shows the energy behavior for the evaluated thermal loads in this section. It can be noted that an increase in ambient or room temperature also caused a rise in the thermal stabilization time and, thus, the percentage of the compressor's start-up increased, resulting in an increase in the total energy consumption. In other words, to maintain the desired temperature, the on/off frequency of the compressor (cycles), as well as the starting time, increased. This happened because the energy consumption increased with the rise in room temperature. Another existing behavior was that when the thermal load rose, and under ambient temperature conditions lower than 20 °C, there was an increase in the number of cycles in one day; this means that the on/off cycles of the compressor were shorter and more common. This is because the change rate of the refrigerator temperature is linked to the food thermal capacity. When the refrigerator is full of food, it causes a greater loss of energy due to the on/off cycles. Therefore, energy consumption increases when thermal load increases, to be able to control the desired temperature.

In Figure 11, the power of the first start of the compressor is illustrated, for the load variation shown in Table 4. Figure 11a shows the difference in both the starting time and the power for a thermal load of 13 kg, which presented an increase from 16 °C to 25 °C in the ambient temperature. This behavior was also observed in the other thermal loads subjected to different conditions of room temperature. For example, for the thermal loads of 20 kg and 30 kg (Figure 11b,d), a greatest increase in the compressor operation time, 5 h approximately, was presented. The thermal load of 30 kg appears to be the condition that prolonged this time the most for the two conditions of room temperature, representing an increase of 0.62 kWh. Hence, the influence of the ambient temperature on the consumed power by the compressor on the first start was confirmed with these behaviors.

Table 4. Energy behavior for different thermal loads.

Thermal Load (kg)	Room Temperature (°C)	Thermal Stability Time (h)	% Switch-On	Total Energy (kWh)	Cycles (24 h)
13	16	24	30	1.4	19
	25	25	39	2.0	34
20	12	24	27	1.3	23
	25	25	42	2.3	34
23	18	22	33	1.9	28
	22	26	35	2.4	33
30	20	24	40	2.1	27
	23	25	44	2.6	23

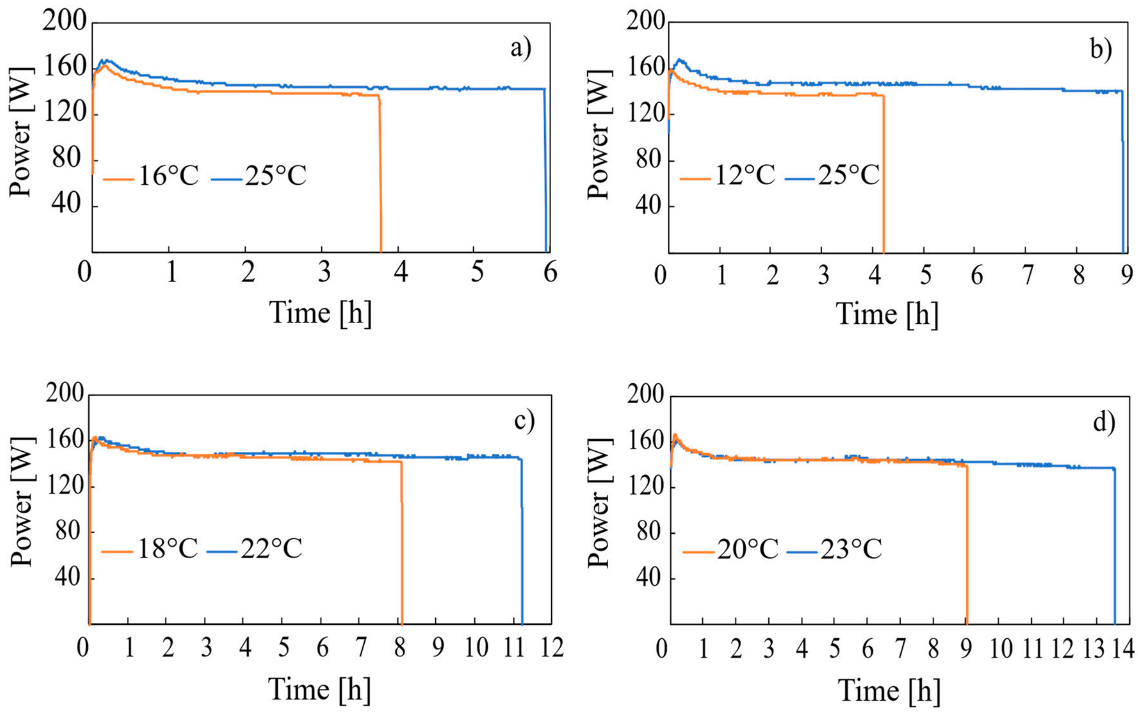


Figure 11. Consumed power in the start of the compressor for different thermal loads: (**a**) 13 kg; (**b**) 20 kg; (**c**) 23 kg; (**d**) 30 kg.

In accordance with the previous sections, the existing importance of the amount of food with regards to the refrigerator energy consumption was confirmed and, to a lesser extent, the effect that this causes in the compartment's thermal behavior. This type of refrigerator works within a range of adequate temperatures for food preservation.

According to the surveys done before this work, only 20% of consumers purchase a refrigerator with the ideal storage capacity (food storage capacity). On the other hand, 100% of consumers ignore the effect of the amount of food and ambient temperature on the appliance performance. In this sense, this type of study should facilitate recommendations through the manufacturer from an energy and thermal viewpoint on how to better use the appliance based on the amount of food and, in general, on the habits of use that cause great increases in energy consumption and that can degrade the food quality due to inappropriate temperatures in the compartments.

Finally, based on the experimental data, a multiple linear regression equation was developed, which shows the combined effect of the ambient temperature (T_{amb}) and the thermal load (L) on the energy consumption (E) for this refrigerator. This equation has a correlation degree of 85%.

$$E = -1.55 + 0.0395m + 0.104T_{amb}. \quad (8)$$

5. Conclusions

In this work, the effect of the thermal load (food) on energy consumption and the thermal condition of the compartments of a domestic refrigerator was experimentally evaluated. The amount of the evaluated thermal load was based on previous surveys applied to consumers to define the amount of food in both compartments. The main objective of this work was to provide more information about domestic refrigeration in term of the effect of the thermal load and the room temperature on the refrigerator performance. For this, a typical refrigerator of 0.3 m^3 was used, where the tests were conducted in triplicate for each assay to achieve reliability. Among the most relevant aspects in this study, the following are mentioned:

- A survey was applied to determine the amount of food commonly stored in the refrigerator compartments. This way, the different thermal loads (from a minimal load of 7 kg to a maximum of 39 kg) were evaluated in this work, an aspect which was not previously justified in the literature.
- The thermal behavior in both compartments of the refrigerator did not show any correspondence with respect to the thermal load increase, while keeping a constant room temperature.
- It was observed that the energy consumption had a great effect due to the thermal load increase where, for example, for an ambient condition of 20 °C, an increase from 0.4 kWh (0 kg as reference) to 3.5 kWh (34 kg) was observed; this increase was from 0.8 kWh (0 kg) to 4.5 kWh (39 kg) for a temperature of 25 °C.
- The first on-state of the compressor increased when the thermal load increased; this behavior was reflected in the refrigerator's total energy consumption.
- For a constant thermal load, the increase in room temperature caused an increase in the temperature of the fresh-food compartment. For a load of 13 kg, the increase in room temperature from 16 to 25 °C caused a rise of 1.5 °C in the food compartment's average temperature. For the case of the freezer, a maximum decrease of 2.6 °C was obtained for a load of 23 kg, whose room temperature increased from 18 to 22 °C.
- Finally, increases in the refrigerator's energy consumption were clearly observed for a constant thermal load and an increase in room temperature.

Author Contributions: Conceptualization, J.M.B.-F. and D.P.-C.; methodology, D.A.R.-V. and Y.H.-A.; resources, M.A.G.-M.; analysis of data, I.H.-P., J.M.B.-F. and D.P.-C. wrote the paper. All authors have read and approved the final manuscript.

Funding: This research received no external funding.

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

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

CC	Cooling load (kW)
COP	Coefficient of performance
Cp	Specific heat (kJ/kgK)
E	Energy consumption (kWh)
h_f	Latent heat of fusion of the of the water (kJ/kg)
m	Thermal load (kg)
Q	Heat removal (kJ)
T	Temperature (°C)
t	Thermal stability time (h)

Subscripts

amb	Ambient
FF	Fresh-food compartment
FZ	Freezer compartment
FZ_1	Heat removal from the initial temperature to the freezing point of thermal load
FZ_2	Heat removal to freeze the thermal load
FZ_3	Heat removal from the freezing point to the final temperature below the freezing point
frost	Referring to ice
water	Referring to water

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