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IMPACT OF PRODUCT LOAD AND THERMOSTAT SETTING IN THE ENERGY CONSUMPTION OF A HOUSEHOLD REFRIGERATOR

Bernardo Junqueira Murta
Pedro Laender
Universidade Federal de Minas Gerais, Departamento de Engenharia Mecânica, Av. Antônio Carlos, 6627 - Pampulha - Belo Horizonte - MG. CEP 31270-901
bjmurta@ufmg.br, pedro-laender@hotmail.com

Luiz Machado
Universidade Federal de Minas Gerais, Departamento de Engenharia Mecânica, Av. Antônio Carlos, 6627 - Pampulha - Belo Horizonte - MG. CEP 31270-901
luizm@demec.ufmg.br

Ricardo Nicolau Nassar Koury
Universidade Federal de Minas Gerais, Departamento de Engenharia Mecânica, Av. Antônio Carlos, 6627 - Pampulha - Belo Horizonte - MG. CEP 31270-901
koury@demec.ufmg.br

Antônio Augusto Torres Maia
Universidade Federal de Minas Gerais, Departamento de Engenharia Mecânica, Av. Antônio Carlos, 6627 - Pampulha - Belo Horizonte - MG. CEP 31270-901
aamaia@ufmg.br

Abstract. *Domestic refrigerator is one of the most energy consuming home appliances, being responsible for up to 30% of the total energy usage in a regular house. The internal temperature of the refrigerator can be adjusted by changing the thermostat position. This adjust is performed by the user, considering only his perception about the requirements of refrigeration of the products. By adjusting the thermostat, the internal temperature set point and the on/off profile is changed. Since the energy consumption of the refrigerator is influenced by the duration of the on/off cycles, this procedure may be better performed if the product load is also considered. The proposal of this work is to identify the electrical and thermal characteristic curves of the refrigerator for different load of product and thermostat position, and evaluate the system power consumption for each case. Several experimental tests were performed using a different number of containers of one liter of water, representing the product load, and adjusting the thermostat in different positions. The thermostat at medium position showed better results evaluating both consumption and temperatures reached regarding food preservation, with energy consumption no much higher comparing to the minimum position.*

Keywords: *household refrigerator, energy consumption, product load, on/off control*

1. INTRODUCTION

It is becoming common sense the awareness about energy consumption throughout the world, creating an attractive market which seeks for best alternatives to overcome the upcoming energy crisis. Climate change, environmental and economic issues are enforcing a major reduction regarding energy consumption in all sectors of society, increasing researches about more efficient electrical equipments in order to minimize, in a short term, the crisis effects.

In 2001, owing to a long dry season in South America, Brazil faced a drastic energy rationing determined by the government to restrain electricity usage to prevent oncoming blackouts (Silva et al., 2007). As a consequence of the drought, the power supply in Brazil experienced a severe lack of production, once 68.5% of the energy generation comes from hydropower plants (EPE 2014). In the beginning of 2015, after another long rain shortage and water misuse by consumers, Brazil faced a similar scenario to that occurred in 2001. The drought brought several issues such as crisis in water supply and energy production, increasing population concern. The government started working on avoiding more severe problems by raising the energy taxes on the most affected areas and creating initiatives as an artifice to force people to reduce the consumption.

According to EPE (2014), regarding the current energy consumption by Brazilians, the residential, industrial and commercial sectors participation are proportionally more impactful when considering the total energy usage, being responsible for 27,0%, 39,8%, 18,1% respectively. Therefore, in order to achieve the purpose of reducing the total amount of energy consumed, any reduction in these three sectors will have a major influence on the overall energy usage in the entire country. To pursue and conquer this goal, it is needed the implementation of more efficient electrical equipments and electronic devices.

The residential electricity consumption in Brazil is responsible for 27,0% of the total energy usage, and the domestic refrigerator has a major participation, being responsible for 30% , together with the electric shower, which is responsible for 20% of the total energy used by the residential sector (GHISI et al. 2007). Regarding the total energy consumed by the entire country, the refrigerator itself has one of the major participation, accounting about 8%. These data indicates that any improvement in these equipments could represent a significant reduction in the global energy consumption.

Household refrigerators cabin temperature is controlled by the thermostat, which setting position command the compressor, turning it on or off. These ON-OFF cycles help to maintain the desired levels of temperatures inside the cabin of the refrigerator, important for food conservation, without the need of a continuous operation that would demand more electricity to the system. However, the cyclic operation also creates energy losses influencing on the overall efficiency (Maia et al., 2013). After shutting off, during the compressor's OFF cycle, the refrigerant can migrates through the capillary tube from the condenser to the evaporator equalizing the system's pressure. This induces efficiency losses since, during the ON cycle, it makes a refrigerant redistribution necessary and rise the evaporator's temperature (Coulter and Bullard, 1997, Björk et al. 2010). According to Rubas and Bullard (1995), in refrigerators without a shutoff valve, this migration effect by reducing the COP by 1.0% times the number of cycles per hour. Wang and Wu (1990) showed, experimentally, that an addition of a shut-off valve prevents refrigerant migration and reduces the compressor power input during start-up and the evaporator's temperature. Furthermore, the start-up procedure of the compressor needs high levels of current, regarding the inductive electric motor inertia, reaching levels 8 to 10 times higher than the nominal current, also contributing to low its efficiency (Outtagarts et al. 1997).

The work conducted by Leva (2010) and Amaral (2013) developed an adaptive on-off control acting filtering the error signal and adjusting the compressor's startup and shutdown moments, improving amplitude and frequency of the temperature oscillation. It was proven that, by reducing the number of cycles, the energy consumption was reduced up to almost 5%. Also, Belman-Flores et al. (2014) proposed a new geometric design for a refrigerator which reduced the number of cycles by 2, and experienced a reduction in the consumption by 10%.

Not only by the compressor off-cycle's effect, the energy consumption of refrigerators has also its efficiency affected by the ambient temperature, product loading, number of door openings and the thermostat setting position (Marques et al. 2014). In this work, a set of tests was run in order to evaluate the effect of the product load and thermostat set point. Measuring the consumption by each thermostat position is the first step to comprehend its operation and improve efficiency.

2. METHODOLOGY

In order to get the experimental data about the consumption of a household refrigerator, a Consul CRC28EBANA refrigerator, with total capacity of 280 liters, was instrumented regarding the temperature on different sections of the refrigerator and electrical parameters of the electric grid, such as current, voltage, active and reactive power, and power factor.

With respect to electrical parameters, the device Kron Multi-K Plus was used to measure voltage and current, and other relevant electrical parameters such as active and reactive power and power factor. Due to current peaks when the compressor is started, it was used a current transformer to protect the device, since it surpasses the measurement range of the device for the current. The collected and calculated data was, then, transmitted to a computer through a serial port.

To evaluate the temperatures inside the refrigerator, a set of T-type thermocouples were attached to different sections in the interior of the household refrigerator (T6 and T7, representing three thermocouples each) , to the compressor (T1 and T2) and condenser (T3 and T4), collecting real time data of desired temperatures, as well as the ambient temperature (T0) as seen in Fig.1. The information received by the thermocouples is collected by a data acquisition system by National Instruments, model N9211 and NI cDAQ-9178, and transmitted to the computer.

The acquired data is processed and stored by a LabView routine. For a synchronized data acquisition between electrical and temperature parameters, was set a sampling rate of 0.5 seconds. Calibration parameters for both thermal and electrical instruments were already included into the program code, which returns the corrected value for voltage, current, active and reactive power and power factor (for the electrical parameters) and the temperatures of each thermocouple attached.

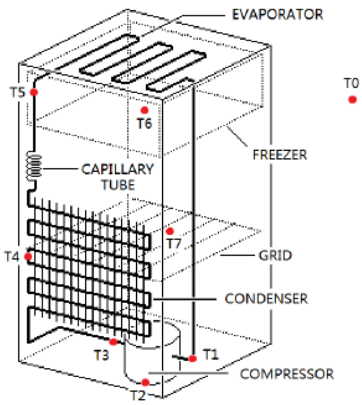
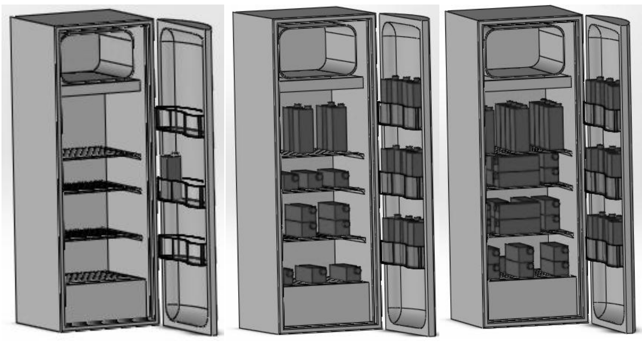


Figure 1: Experimental apparatus showing the position of some thermocouples attached. (Source: Amaral, 2013b)

Aiming to get information about the electrical consumption of a household refrigerator, a set of tests were done for each thermostat's set up position for a predetermined thermal load in its interior. The thermostat position for each run followed the fabricant marks indicating Minimum, Medium and Maximum positions. Furthermore, for each thermostat position, the product load, represented by reservoirs containing 1 liter of water, was also varied in order to get a relationship between the electrical consumption and the product load. Previous tests showed similar results when evaluating oncoming loads. For this reason, 3 different loads were chosen, representing 0, 30 and 50 liters of water, disposed according to Fig.2.



(a) (b) (c)

Figure 2: Experimental sketch showing the reservoir disposal used. (a) 0 liter; (b) 30 liter; (c) 50 liter.

Tests were initiated with temperatures inside the cabinet of the refrigerator equivalent to the room temperature, cooling from this point to the temperatures controlled by the thermostat position, until the ON-OFF cycles were considered in a steady state region.

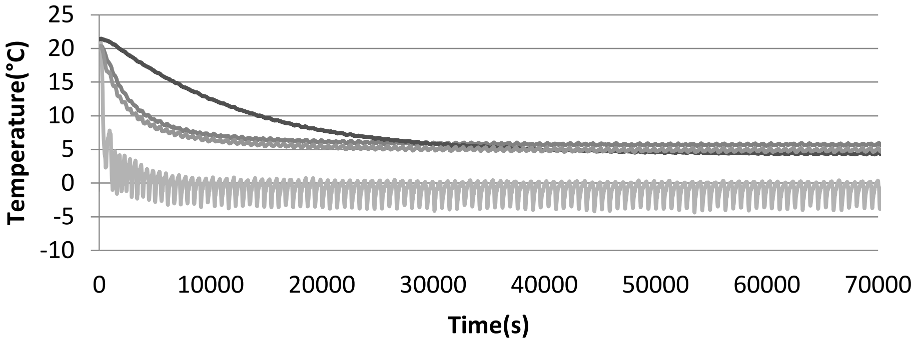
The temperatures data was used to determine the steady state region, considered to be when the ON-OFF cycles do not cause a significant decay in the temperature next to the thermostat. In a time range of 20000 seconds, the test was considered in a steady state region if the temperature varied less than 0.5°C. This analysis needed to be done in order to shorten the time of the tests.

For each experimental run, a time range of 20000 seconds, in steady state, was then analyzed. The electrical consumption analysis was done considering the information about the active power, since its graph area represents the total energy consumed (in Joules). The graph area was calculated using the trapezoid rule method, enabling the determination of the amount of energy consumed point to point. The energy consumed is then converted to kWh to compare each test regarding both thermostat set up position and different load.

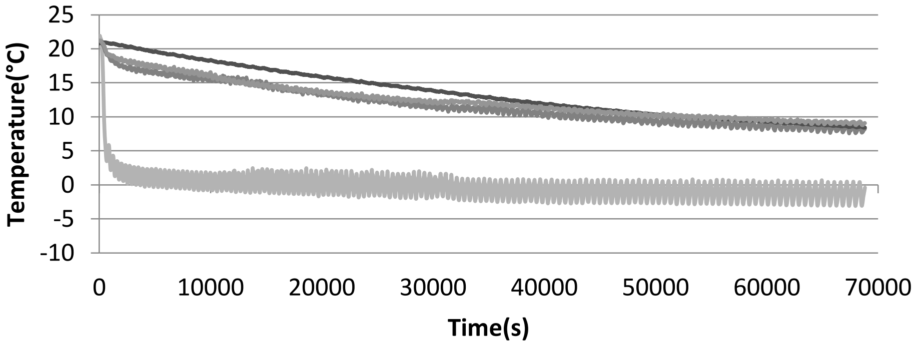
3. RESULTS AND DISCUSSIONS

3.1 Electrical Consumption Evaluation

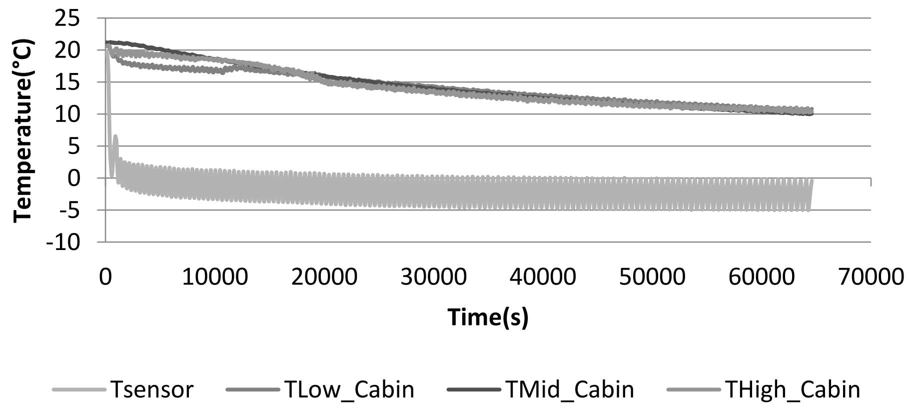
Several experiments were performed for different setting positions for the thermostat and different product load. The experimental time was determined evaluating the mean temperature decay indicated by the thermocouple attached next to the thermostat temperature sensor indicating a steady state region. This evaluation is difficult to determine since it seems to keep reducing its mean temperature in longer tests. Figure 3 shows the temperature graphs for the thermostat on the Minimum position for each load. The ON-OFF cycles represented are measured by the thermocouple attached next to the temperature sensor. Inside the cabin of the refrigerator, are attached 3 others thermocouples to check the temperature for food preservation, represented by High Cabin, Mid Cabin and Low Cabin, attached to a position right below the evaporator, a water reservoir at the door and at the bottom of the refrigerator, respectively.



(a) 0 liter product load



(b) 30 liter product load



(c) 50 liter product load

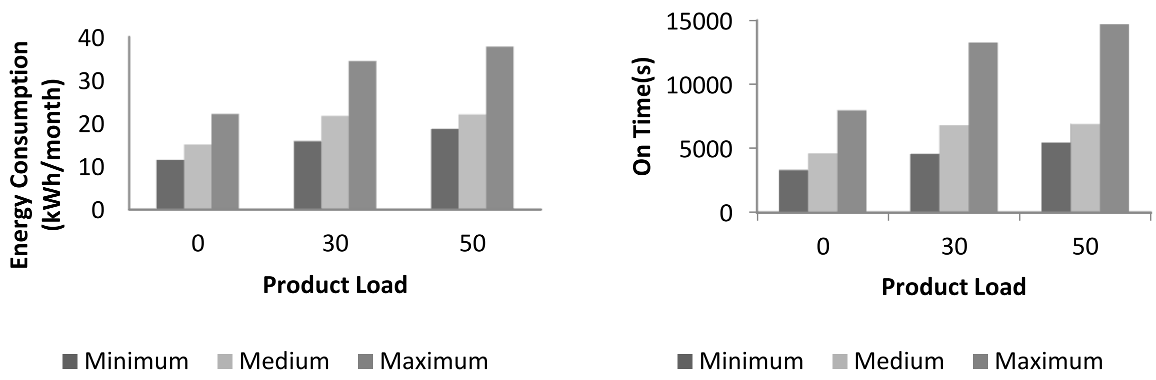
Figure 3: Experimental data regarding temperatures in 4 different positions inside the refrigerator: temperature sensor, high, mid and low cabin. All graphs performed with thermostat at minimum position and room temperature in between 18°C and 20°C;

The experimental data for the minimum position of the thermostat shows a temperature range of approximately 5°C, determining the compressor startup and shut-down, which creates ON-OFF cycles. Also, when increasing the product load, is observed a better accordance among all cabin temperatures in the beginning of the test and with a slower response, due to the thermal inertia introduced by the product load. The Mid Cabin final temperatures, representing the temperature of a water reservoir placed at the door, after 65000 seconds are 4,44°C, 8,85°C and 10,05°C for 0, 30 and 50 liter loads respectively. The high temperatures indicate a problem when it comes to food preservation, which exceeds the maximum temperature recommended, approximately 8°C (Marklinder et al., 2004a).

From the electrical data, information about the active power was used to calculate the electrical consumption, point to point, using the trapezoid method. After obtaining the area of the graph, it was taken a range of 20000 seconds for all the tests and calculated the total energy consumed during this period. The results are shown in Tab. 1 and Fig 4

Table 1 – Energy consumption for each load and respective thermostat set up position

Load/Setting Position	Wh	kWh/month	Energy per mass (kWh/kg.month)
0Min	16.00	11.51	11.51
0Med	20.90	15.07	15.07
0Max	30.80	22.14	22.14
30Min	22.00	15.86	0.51
30Med	30.20	21.75	0.70
30Max	47.80	34.42	1.11
50Min	26.00	18.70	0.37
50Med	30.70	22.07	0.43
50Max	52.50	37.79	0.74



(a) (b)

Figure 4: Experimental results for each product load and thermostat position regarding (a) energy consumption per month and (b) the ON time for the compressor during the 20000 seconds analyzed.

From Table 1 and Fig.4 it is seen that, in a range of 20000 seconds (5.55 hours) the thermostat being positioned on the Maximum will result in a greater electrical consumption, followed by the Medium position and the Minimum position, for all amount of product load. The same relation is observed when evaluated the time that the compressor was on. The fact of the higher consumption at maximum position of the thermostat is due to the lowest temperatures reached at the evaporator, which takes longer to attain. Experiments showed that 1°C reduced in the evaporator, increased in up to 8% the total energy consumed (Saidur et at., 2002).

Analyzing the tests at the medium position for the thermostat, its seen, in figure 4, that the product had a minor influence on the energy consumption, with ON times close to each other. Also, the number of cycles was shown exactly the same for the tests with 30 and 50 liter of product. This result, regarding the temperature reached for food preservation, might be the best case, since it does not consume much energy in comparison with the minimum position, but with lower temperatures inside the cabin. Further analyses are discussed in section 3.3.

The energy consumed if analyzed by kilogram of product it's seen that, at maximum position for the thermostat, the energy consumed is much greater. In fully capacity, though, the medium position needs a small amount of energy reaching lower temperatures, comparing the minimum and medium positions.

3.2 Active Power Analysis

Figure 5 shows a test of the active power data, for 0 liter product load and thermostat position at Minimum, displaying peaks of current (consequently active power) during the compressor startup, due to the inertia of the motor.

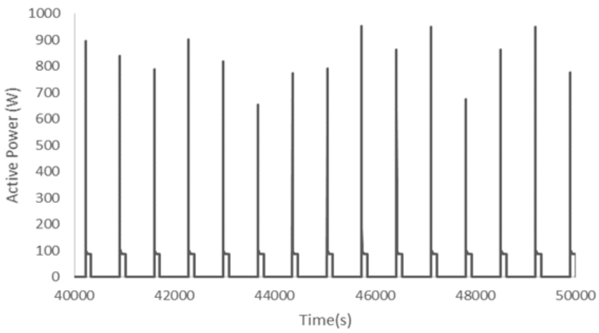
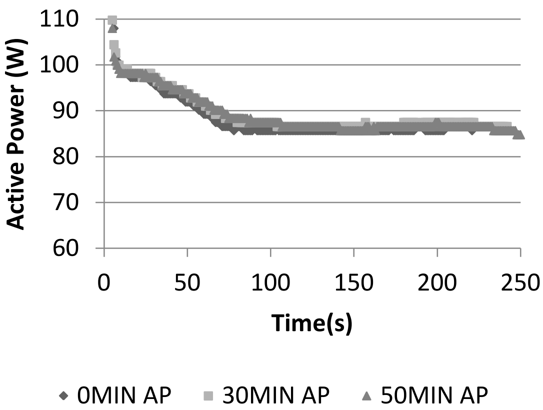
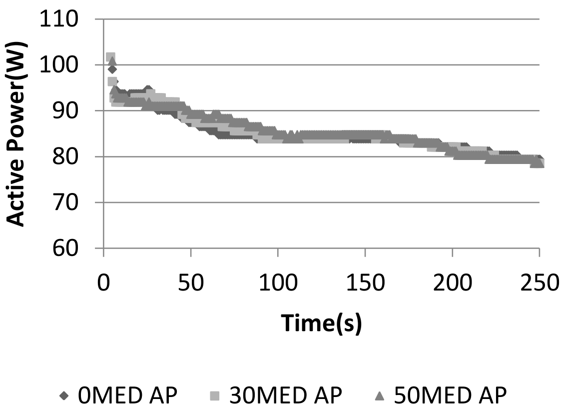


Figure 5: Active Power in function of time

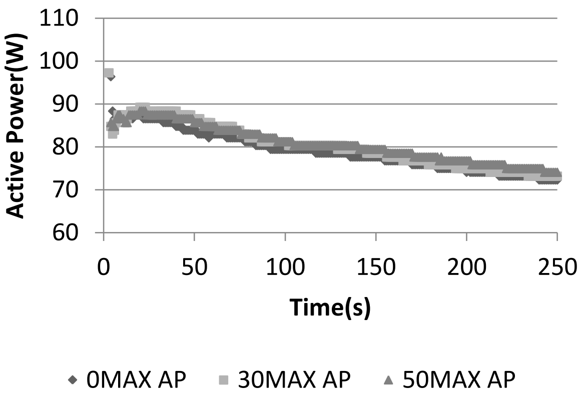
It was shown from Tab. 1 and Fig. 4 that the ON time for each experiment, regarding thermostat position and load, were different in comparison to all the others, but also showed some relationship among the experiments run at a certain position of the thermostat. Figure 6 shows the behavior of the active power for all thermostats positions studied against the load variation for just a cycle during the steady-state condition.



(a)



(b)



(c)

Fig.6: Active Power behavior against load variation for each thermostat setting position (a) minimum, (b) medium and (c) maximum.

Analyzing only the active power for each thermostat position, it’s seen in Fig.6 a small influence of the load in the active power during the transient state after the large peak of current in the beginning of each cycle, not observed during the cycle steady-state condition. Despite having the major energy consumption, as calculated, the Active Power is lower at the Maximum position of the thermostat, and higher at the Minimum position. This fact is explained by the variation of the volumetric efficiency and cooling capacity at different temperatures of evaporation. For higher temperatures, the volumetric efficiency and the fluid flow rate on the entrance of the compressor increases, which increases the cooling capacity. At lower temperatures, the volumetric efficiency of the compressor decreases, and so the fluid flow rate and, then, cooling capacity. This effect also influences the COP, which is greater for higher temperatures of evaporation. The behavior observed in Fig. 6, since the work temperatures for the minimum position are higher than for the other thermostat positions, was then expected. Therewith, as seen at Fig. 4, the ON time is a dominant factor that influences the overall energy consumption, since the ON time for the Maximum position are much greater than for the others thermostat positions.

3.3 Food Preservation Temperature Analysis

Apart from evaluating the energy consumption, the food preservation needs a priority attention. Most kinds of foods are said to be preserved in a refrigerator at maximum temperature recommended of 8°C (Marklinder et at. 2004b). From Fig.3, it’s seen that, cooling from ambient temperature (20°C) with a thermostat position at Minimum and 50 liter load, it takes approximately 65000 seconds (18h) to reach 10°C at the water reservoir placed at the door (Mid Cabin), which is still far from the optimal temperature of conservation. Another test performed with 36h was able to low its temperature to 6.4°C, Fig. 7.

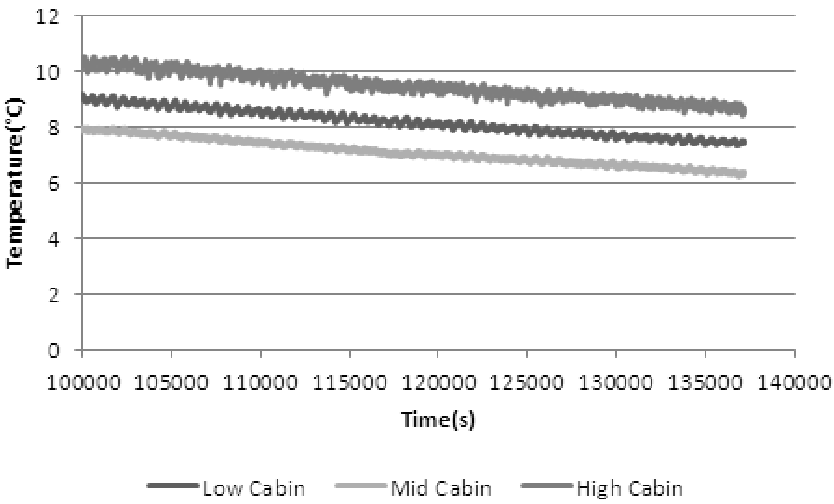


Figure 7: 36h test showing the temperatures at Low Cabin, Mid Cabin and High Cabin

In order to evaluate the quality of food preservation for the Minimum thermostat position, and even the Medium and Maximum positions, other tests should be run, without the need of the starting point at the ambient temperature. As well as evaluate the influence of the door opening in the energy consumption and in the temperature inside the refrigerator’s cabin. For all tests, the temperature of the water at the door was taken after 65000 seconds, and it can be seen in Tab. 2. These data indicates the need of attention for food preservation in all thermostat setting positions when loaded with fully capacity.

Table 2: Product Temperature after 65000 seconds

Load/Setting Position	Temperature at 65000s (°C)
0Min	4.44
30Min	8.85
50Min	10.05
0Med	1.85
30Med	6.51
50Med	7.00
0Max	-3.25
30Max	1.10
50Max	4.81

Gathering all the information about consumption and temperatures for food preservation, it can be determined that the medium position for the thermostat is the best solution, depending on the type of food to be preserved. The temperatures reached for this position are below the one recommended of 8°C. Nevertheless, lower temperatures are more efficient for preservation and some kinds of food needs lower temperature for storage.

4. CONCLUSIONS

In this work it was shown aspects of the energy consumption of a household refrigerator in regards the thermostat position and the product load. Varying the thermostat setting position and the amount of product loaded inside the refrigerator it was noticed a variation on the number of ON-OFF cycles of the compressor, as well as the ON time for the cycles. The thermostat at maximum position demonstrated greater energy consumption when comparing to the other positions, but with lower temperatures reached inside the refrigerator's cabin. Lower temperatures of evaporation also explain such consumption since it affects negatively the COP of the refrigerator.

When evaluating temperatures for food preservation, it was noticed that the thermostat at minimum position may not be qualified, taking 36 hours to reach 6.4°C when initiated at room temperature, being not adequate for food preservation. Despite reaching a value below the recommended, the time for reaching the desired temperature is critical.

The thermostat at medium position showed better results when it comes to both energy consumption and temperature levels for food preservation. Its consumption is no much higher comparing to the minimum position, and being capable of reaching lower levels of temperature below the recommended.

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