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ANALYSIS OF THE POWER CONSUMPTION OF A HOUSEHOLD REFRIGERATOR WHEN USING A DIGITAL FILTER IN THE CONTROL CIRCUIT

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Abstract. *When evaluating the domestic energy consumption, the refrigerator is among the household appliances with the largest participation. In this way, any improvement in the performance of this equipment will result in a considerable improvement in the overall energy consumption. In this work, it was employed a digital control system in a household refrigerator to reduce the frequency of on-off cycles and improve the relation between on-off cycle time. The system consists of a digital filter inserted into relay starting circuit. This filter has the function of altering the error signal characteristics that defines the time of starting or stopping the compressor. After assembling the system, were performed several tests in order to evaluate the control methodology effectiveness with respect to energy consumption. With this device, it was achieved a reduction of up to 4.7% in the power consumption of the refrigerator.*

Keywords: *on-off control; household refrigerator; digital control; digital filter*

1. INTRODUCTION

Since the last few decades, globalization has brought new standards of consumption for developing countries, which is increasing the demand for energy. The quest for energy efficiency improvement in the equipment is a natural process with gradual awareness of society with regard to sustainability. These factors have motivated research to identify the most energy-consuming equipment and ways to make them more energy-efficient.

According to the National Energy Balance (BEM, 2012), the residential sector consumed 23.4% of all energy produced in Brazil in 2011 and, 41.7% of this amount was originated from electrical source. The household refrigerator is between the most energy consuming household appliances and it is responsible for 32% of residential electrical consumption. Therefore, any improvement in the performance of this equipment will cause a major low in global energy consumption. In view of this, intensive efforts have been taken in the search for solutions to improve the energy efficiency of refrigerators without changing their potency. One of the solutions is to override the capacity control performed through the start up a shutdown of the compressor by the capacity control performed by controlling the compressor rotational speed. According to Binneberg (2002), 69% of the losses in the refrigeration cycle are from the compressor and the electric motor. Through numerical simulation, Binneberg (2002) showed that the use of variable speed compressors could lead to energy savings of up to 30%, when compared with refrigeration systems that employ on/off control. Coulter (1997) showed that during the cyclic operation, the refrigerator operates between 5% and 25% less efficient than the corresponding quasi-steady state machine. By reducing the cycling frequency, it is possible to improve the system's efficiency without increase the energy consumption. There are already commercial compressors with speed controllable, but it still has a discouraging cost, at least for the low-income domestic consumers.

Bearing in mind that the cyclic operation is one of the main causes of efficiency loses in the household refrigerator, Leva et al. (2010) developed an adaptive on-off control that basically acts filtering the error signal and adjusting the better time to switch on or off the compressor, in order to improve the amplitude and the frequency of the temperature oscillation. By using this strategy, it is possible to reduce the number of on-off cycles and reduce the difference between the set point and the process variable. Despite intending to improve the performance of the on-off actuation, Leva et al (2010) did not evaluate the impacts of the proposed control strategy in the refrigerator's energy consumption.

In this work it was designed a digital filter similar to the one proposed by Leva et al. (2010), to be installed in a household refrigerator in order to reduce the number of on-off cycles of the compressor. The digital filter was programmed in a microcontroller and a circuit board was designed, built and installed in a domestic refrigerator. After mounting the system were conducted some experimental tests in the refrigerator for validation of their effectiveness with regard to energy consumption. In this way, the work becomes important as a new strategy of energy saving may be adopted in respect of domestic refrigerators, energy saving and contributing to a sustainable development.

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2. EXPERIMENTAL APPARATUS

The experimental test bench consists of a Consul refrigerator, model CRC28EBANA, with a volume of 280 liters. The compressor is hermetic type, model Tecumseh THK 1330YDS. This compressor operates on a voltage range from 100 to 140V and 60 Hz. The motor type is PTCSIR and its rated power is (+/ -5%) 75 W according to the manufacturer. The refrigerant fluid is the R-134a.

To monitor the refrigerator temperature, eight T-type thermocouples were installed, distributed into the following points: air, compressor inlet, compressor base, compressor outlet, condenser middle, air inside refrigerator cabinet, evaporator inlet and air inside freezer. The arrangement of these thermocouples can be seen in Figure 1.

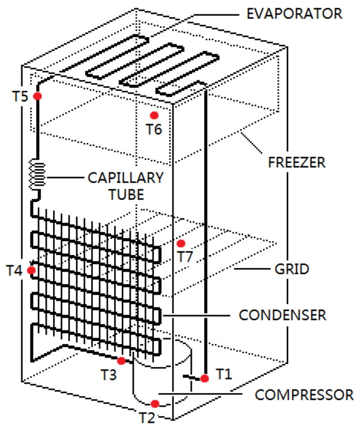

Figure 1. Arrangement of the thermocouples at the refrigerator

The temperature data were collected using a data acquisition system that consists of a chassis (NI cDAQ NI-9178) on which were installed four modules N9211 to connect the thermocouples. The thermocouples were placed in the refrigerator in order to allow the temperature reading at the inlet and outlet of each component and in some specific points inside the cabinet and on the compressor housing. In order to keep the refrigerator as the manufacturer provided it, thermocouples were installed on the walls of the tubes. To measure the temperature data needed in the control board, it was employed a LM335 circuit. This sensor was connected directly in the circuit board and installed close to the place in which the manufacturer installed the refrigerator's thermostatic sensor.

To measure the electrical data, it was used a multimeter KRON, model Mult-K Plus. With this meter, it was possible to evaluate the voltage, current, power factor and active and reactive powers. Since the current can reach values that exceed the maximum value supported by the KRON multimeter, it was used a transformer to reduce the current through the meter. This transformer reduces the current to a third of the original value.

The communication between the data acquisition system and the computer was established using a USB cable. It was developed a graphical user interface using the LabView program, as well as the routines that allowed the automation of measurement, processing and storage of all data into a computer.

3. METHODOLOGY

The temperature control in household refrigerators is typically performed by using a relay feedback, as shown in Figure 2. This control methodology drive the system to a permanent oscillation around the set point.

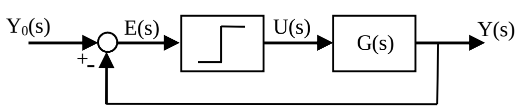

Figure 2. Typical relay feedback control

Leva et al (2010) showed that the oscillation amplitude and frequency could be controlled by adding a filter in the control system scheme, before the relay, as showed in the Figure 3. By controlling the oscillation amplitude and frequency, it is possible to reduce the error and control the number of cycles of compressor on-off.

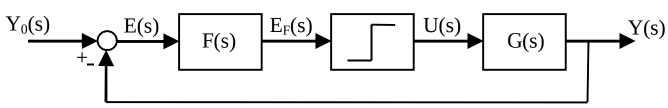

Figure 3. Block diagram with the typical relay feedback control and the filter

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The filter transfer function is presented in EQ. (1). In this equation, the parameters T_z and T_p can be changed in accordance with the desired temperature profile (Leva et al., 2010).

$$F_{(s)} = \frac{1 + sT_Z}{1 + sT_p} \tag{1}$$

To evaluate the effectiveness of this approach, one digital filter based on the filter proposed by Leva et al. (2010), was designed and programmed in a microcontroller. An electronic board was constructed and used as a replace to the original relay starting circuit. From EQ. (1), by applying the inverse Laplace transform, EQ. (2) can be written as follows:

$$T_p * \frac{d_{y(t)}}{d_t} + y(t) = u(t) + T_z * \frac{d_{u(t)}}{d_t} \tag{2}$$

From EQ. (2), it is possible to obtain EQ. (3), where $y_{(k)}$ is the filtered value, $u_{(k)}$ is the measured temperature value, and Δt is the change in time.

$$y_{(k)} = u_{(k)} * \frac{(T_z + \Delta t)}{(T_p + \Delta t)} - u_{(k-1)} * \frac{T_z}{(T_p + \Delta t)} + y_{(k-1)} * \frac{T_p}{(T_p + \Delta t)} \tag{3}$$

In this work, three different values for T_p were utilized: 35, 55 and 75. The T_z variable was kept as being one in all tests. These values were chosen because, during simulations performed using MATLAB, they did not promote significant change in the maximum and in the minimum cabinet's internal temperature, but reduced the number of on-off cycles.

To evaluate the control system performance, four tests were carried out. Each test consisted in monitoring the refrigerator temperature and electrical data during about 36,000s (10 hours). In the beginning of all tests, all parts of the refrigerator were at room temperature, the door was kept closed and the refrigerator was completely empty. In Table 1 is presented the conditions in which each test was performed.

Table 1- Initial test conditions

Filter	Room temperature (°C)	Cabinet internal temperature (°C)	Tz	Tp
Without filter	22.2	21.8	-	-
Filter 1	21.5	22.5	1	35
Filter 2	22.7	22.1	1	55
Filter 3	22.0	21.8	1	75

4. EXPERIMENTAL RESULTS

The first test was performed to characterize the temperatures in which the compressor switches on and off. By analyzing the temperature and current curves during the full system operation (Figure 4), the values established for T_{max} and T_{min} were -9.4°C and, -13.6°C respectively.

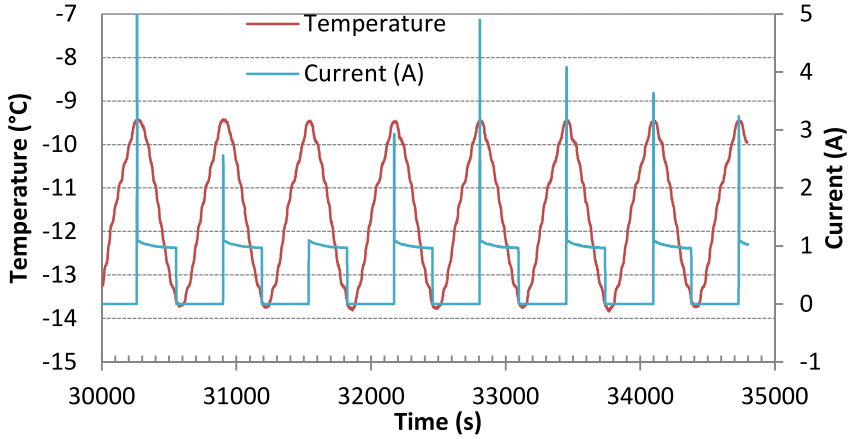

Figure 4. Temperature and current behaviour dring the full system operation.

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When the compressor is switched off, part of the refrigerant fluid at high pressure and high temperature in the condenser and in the liquid line, migrates to the evaporator (Murphy et al., 1986). Despite the fact that this fluid migration be one of the factors that reduces the system efficiency, this phenomenon reduces the condenser pressure and contributes to make easier the next compressor start-up. With the purpose of understanding the pressure behavior, the saturation temperature in the condenser and in the evaporator were used to estimate the condensing and the evaporating pressure, by employing a polynomial equation elaborated using the refrigerant fluid data (R134a) extracted from Borgnake (2000).

$$P_{sat} = 10^{-10} * T_{sat}^{6} - 2 * 10^{-9} * T_{sat}^{5} + 10^{-6} * T_{sat}^{4} + 9 * 10^{-4} * T_{sat}^{3} + 0.149 * T_{sat}^{2} + 10.61 * T_{sat} + 293.58 \quad (4)$$

In order to avoid overloading the compressor due to high pressures during the start-up, the condensing and evaporation pressure were analyzed during the compressor shut down and start-up, considering the full system operation. Figure 5 presents the pressure evolution, obtained using EQ.(4), after the compressor shut down, during the full system operation. As mentioned before, the condensing pressure reduces and the evaporation pressure increases until the new compressor start-up. From this point, the condensing pressure rises and stabilizes close to 1000kPa and the evaporation temperature stabilizes near to 100kPa.

As the main objective of this work is to reduce the consumption by decreasing the frequency of cycles, it is expected that by using the controller presented in this work, the off cycle will increase. However, to protect the motor from any possible error, it was settled in the code that the compressor could only be started after a minimum of 200s from the last shutdown.

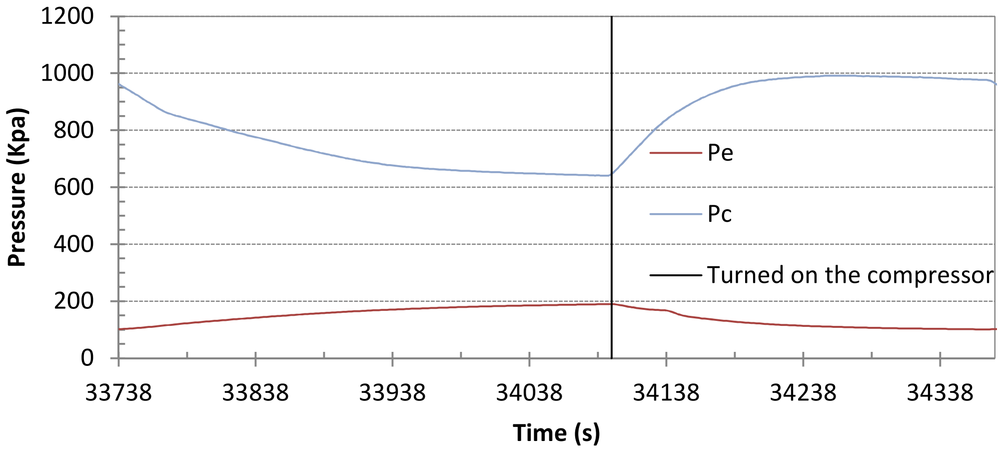

Figure 5. Pressure evolution during the compressor shutdown and start-up considering a full system operation

In Figures 6 to 9 are represented the pressure in the condenser and in the evaporator and the refrigerator power. The vertical line marks the instant that occurs the first peak of the first complete cycle in the selected range (32,400s to 36,000s). The power is represented only in order to facilitate the visualization of when the compressor is turned on (consumption ≠ 0) and turned off (consumption = 0). In Table 2 are exposed the numerical pressure values at the compressor start-up and in the first peak after the compressor start-up as well as the time in which these measurements took place. By comparing the pressure values for the system without filter with the system with the filter it was verified a small reduction in the restart pressure (2.2%, 1.7% and 2.5%) and a small variation in peak pressure (0.5%, -1.1% and -1.1%). The reduction in the start-up pressure occurs due to the longer period that the compressor was kept turned off. Therefore, there was more time to equalize the pressure. Additionally, it can also be observed that all pressure peaks take approximately 160s to occur. According to Coulter and Bullard (1995) after the compressor shutdown there is a refrigerant migration, going from the condenser (high-pressure region) to the evaporator (low-pressure region). This implies in an increase in the evaporator temperature and in a decreases in the condenser temperature. After the system start-up, the compressor spends about 160s to reestablish the appropriate temperature and pressure.

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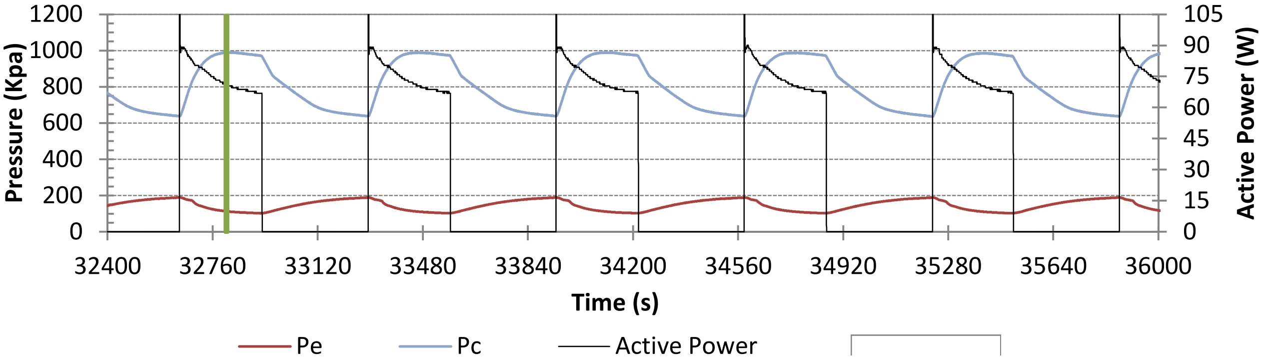

Figure 6. Pressure and power evolution (without filter).

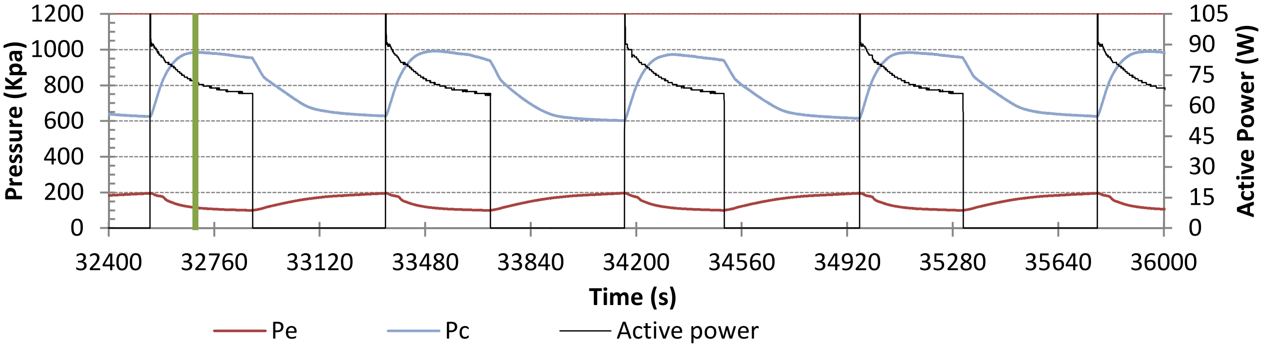

Figure 7. Pressure and power evolution (filter 1).

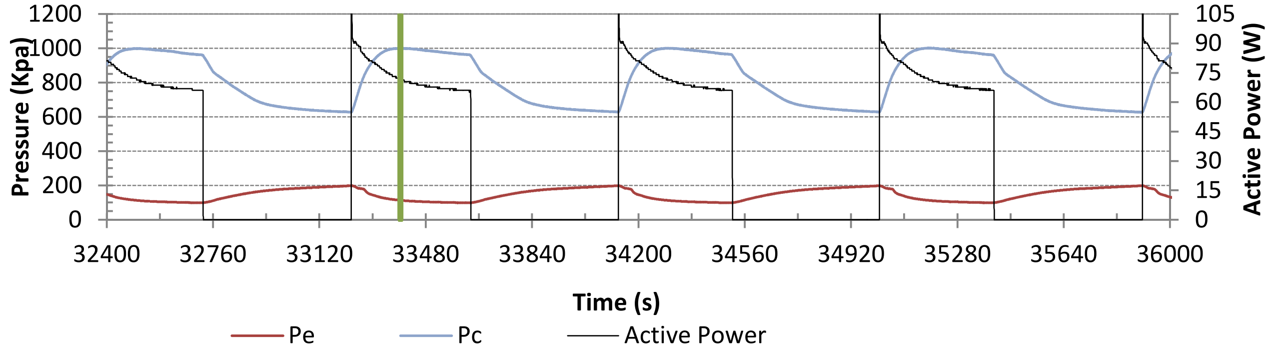

Figure 8. Pressure and power evolution (filter 2).

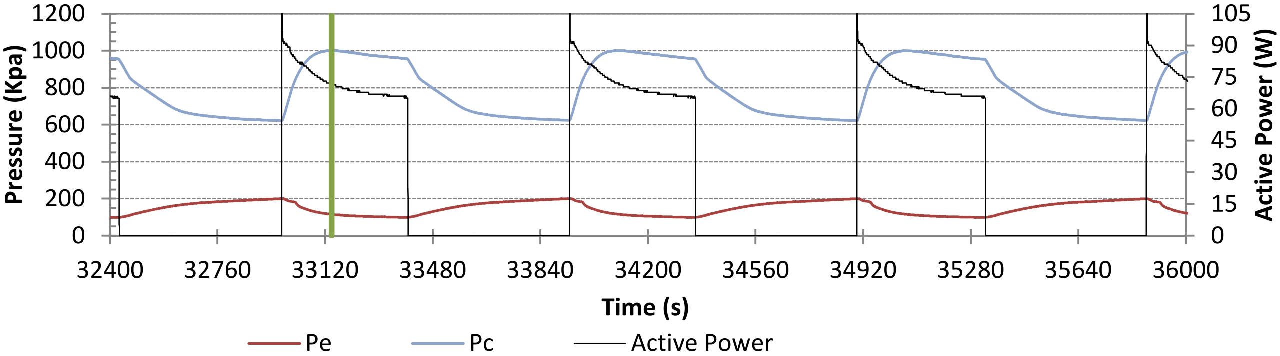

Figure 9. Pressure and power evolution (filter 3).

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Table 2. Pressure and time during the restart and peak time

Tests	Restart Time (s)	Peak Time (s)	Restart pressure (kPa)	Peak pressure (kPa)	Time between the restart and the peak(s)
Without filter	32.647,0	32.807,0	639,0	989,0	160,0
Filter 1	32.541,5	32.695,5	625,1	983,7	154,0
Filter 2	33.229,0	33.394,5	628,1	1.000,2	165,5
Filter 3	32.974,0	33.141,5	623,2	1.000,1	167,5

In Figure 10 is presented the temperature evolution during the interval from 0 to 36,000s. In the test without the filter, the first compressor shutdown happened about 20 to 25 min earlier than system with the filter, in a temperature higher than the temperature used as a reference to turn off the compressor during the full system operation. The temperature limits (T_{max} and T_{min}) achieved during the test without the filter decreased until they reach a constant track in which T_{max} =-9.4 and T_{min}=-13.6. This event happens just few times, when the refrigerator is kept turned off during time enough to all parts achieve the room temperature, like when it is turned on for the first time, or after cleaning or defrosting. When using the filters, in all cases, in the first shut down the temperature is at the desired inferior limit.

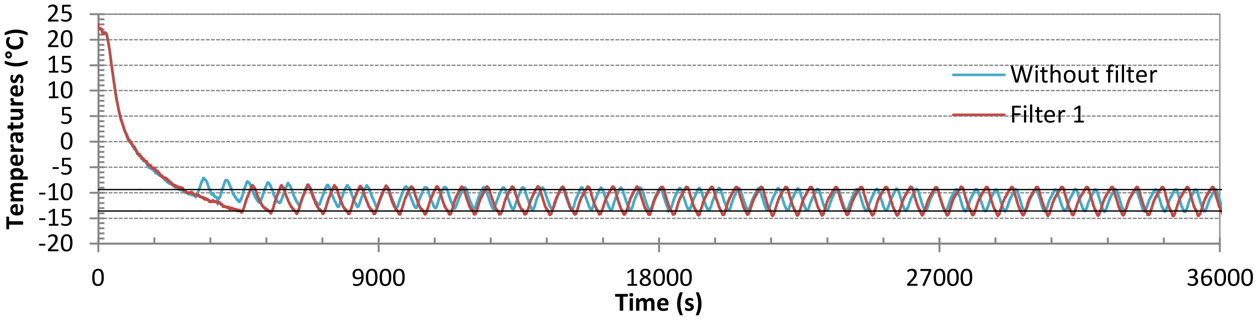

Figure 10. Comparison between the temperature evolution in the test without filter and the test using filter 1.

In Figures 11 to 13 is presented a comparison between the temperature profile when the refrigerator is operating with and without the filter. The maximum temperature variation (upper range) between the system without the filter and the system with the filter was 0.4° C, 0.8° C and 0.9° C, and the minimum temperature variation (lower amplitude) was 0.8, 0.9° C° C and 1.0° C, when using filter 1, 2 and 3, respectively. It is important to highlight the need of a posterior analysis to find out if this temperature variation could compromise the food conservation.

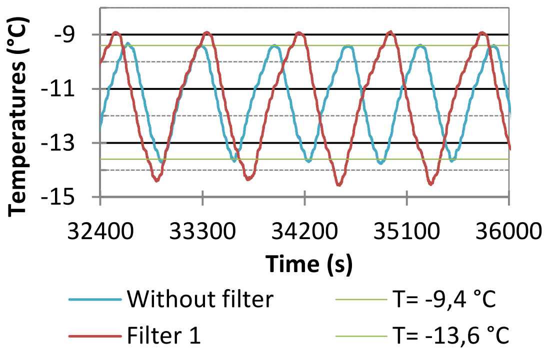

Figure 11. Comparison between the temperature evolution in the test without filter and in the test using filter 1.

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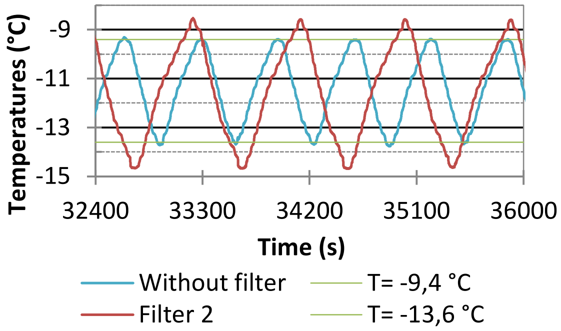

Figure 12. Comparison between the temperature evolution in the test without filter and in the test using filter 2.

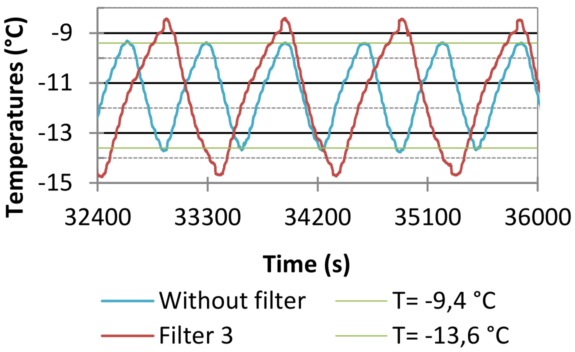

Figure 13. Comparison between the temperature evolution in the test without filter and in the test using filter 3.

In Table 3 is presented the compressor's total time of operation. Having as reference the system without the filter, the use of the filter increases the time that the refrigerator is connected in 4.1%, 3.1% and 2.7%, considering the filters 1, 2 and 3, respectively. Considering only the tests using the filter, there is a reduction in the time in which the compressor is connected when the T_p is increased. The behavior depicted in Table 3 occurs only when is considered the first instants of the refrigerator operation, when the thermostat is still adjusting to a large change in the temperature. In the first cycle of operation, the compressor is switched off before it reaches normal operating temperature. The impact of this fact in the results is significant if is considered the duration of the tests of this work. This difference will become little representative if the operating time considered is greater.

Table 3 – Compressor's total time of operation (0-36,000s)

	Time off	Time on	Total Time	Total on time
Without filter	17.188	18.812	36.000	52,26%
Filter 1	16.420	19.580	36.000	54,39%
Filter 2	16.607	19.393	36.000	53,87%
Filter 3	16.685	19.315	36.000	53,65%

In table 4 is presented the compressor's operation time, during the full system operation. Having the system without the filter as reference, in all cases the filter provided a reduction in the on time of 0.2%, 1.2% and 1.8%, considering filters 1, 2 and 3, respectively.

Table 4 - Compressor's total time of operation (18,000-36,000s)

	Time off	Time on	Total Time	Total on time
Without filter	9.886	8.114	18.000	45,08%
Filter 1	9.901	8.099	18.000	45,00%
Filter 2	9.984	8.017	18.000	44,54%
Filter 3	10.034	7.967	18.000	44,26%

In Figure 14 is presented the total of on-off cycles observed during the 18,000-36,000s of the test. By analyzing this figure can be verified that an increase in T_p promotes a decrease in the number of cycles. The most representative reduction was of 37%, when the system without the filter was compared with the system using the filter 3. The filter acts changing the error signal, becoming the maximum values bigger and the minimum values smaller. Creating this effect, the filter changes the time on-off the compressor, which reduce the frequency of cycles.

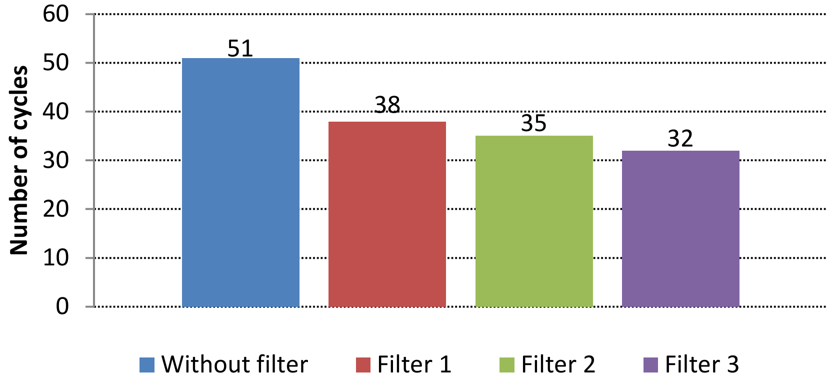

Figure 14. Total of on-off cycles observed during the 18,000-36,000s of the test.

In Figures 15 to 18 is presented the evolution of the active power considering the period of 0-36,000s. Analyzing the curves one can see once again the decrease in the number of cycles with the increase of T_p.

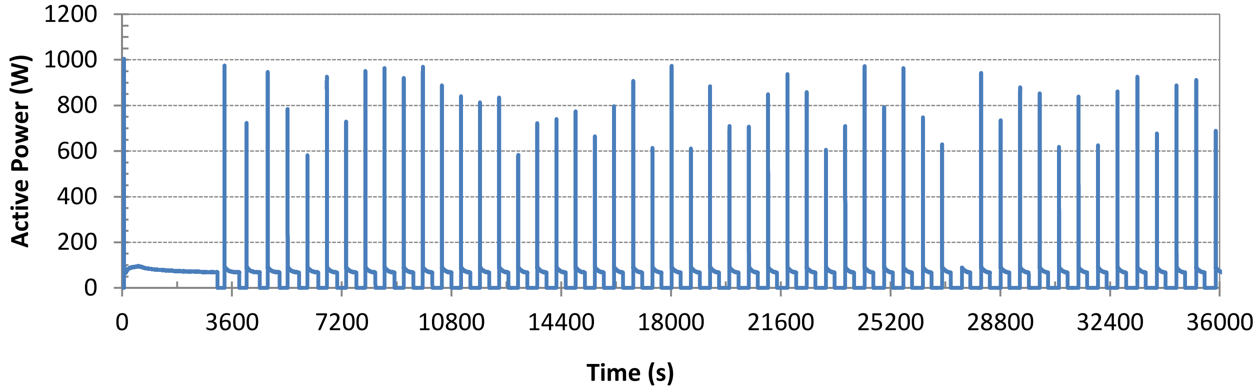

Figure 15. Active power considering the period of 0-36,000s (Without filter).

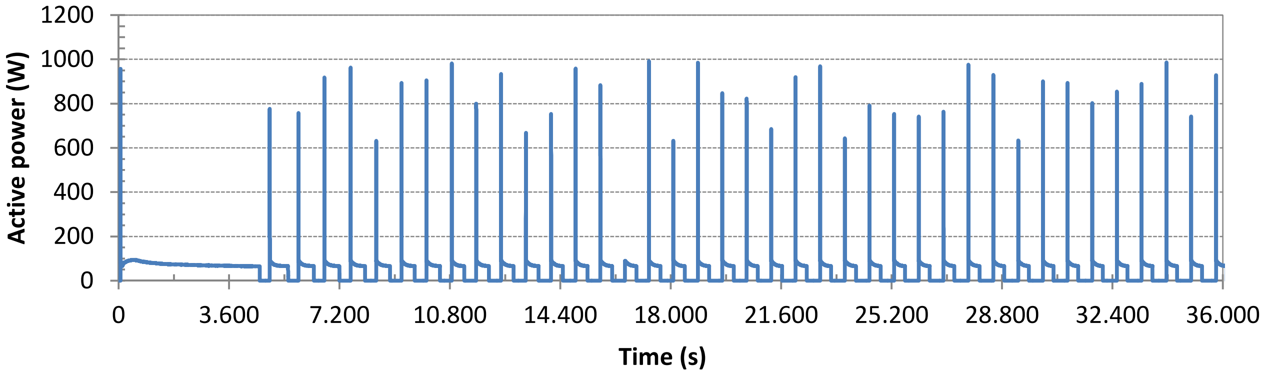

Figure 16 – Active power considering the period of 0-36,000s (Filter 1).

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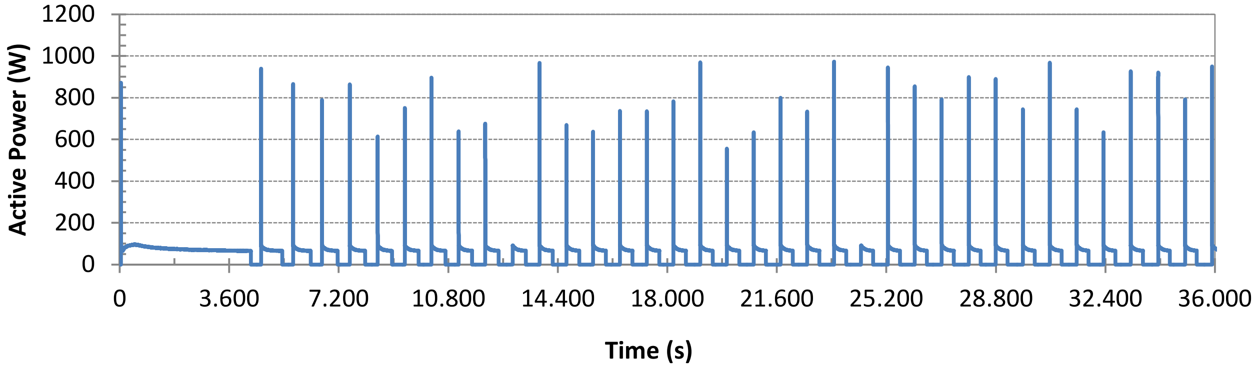

Figure 17 – Active power considering the period of 0-36,000s (Filter 2).

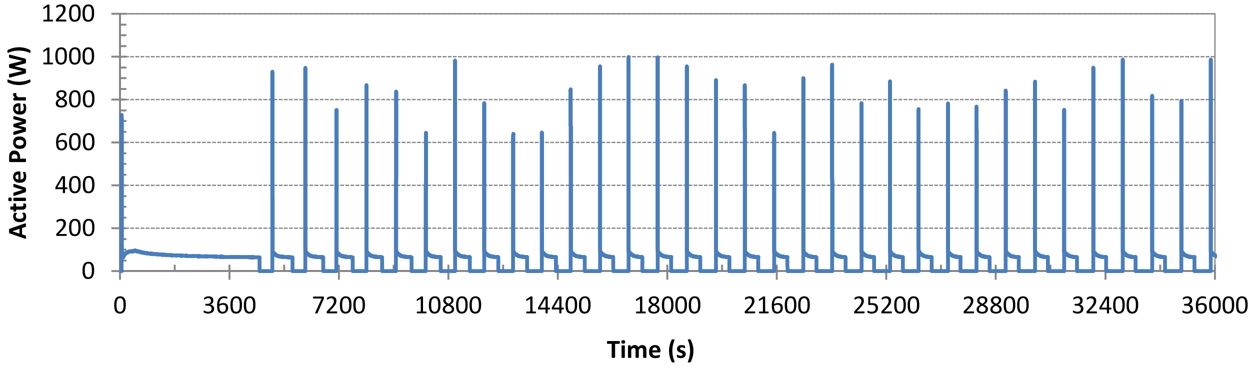

Figure 18 – Active power considering the period of 0-36,000s (Filter 3).

The curves presented in Figures 15 to 18 were integrated utilizing the trapezoidal rule integration in order to determine the total consumption. In Figure 19 and 20 is presented the total energy consumption in Joules. In the Figure 19 the limits of integration are from 0 to 36,000 and in the Figure 20 are from 18,000 to 36,000s. In Figure 19 is shown that there is little variation in the consumption with regarding to the system without the filter (% -0.78, 0.36% and 0.71% for the filter 1, 2 and 3, respectively). This phenomenon may be due mostly to the fact that the compressor is turned off at the first time before it reached normal operating temperature.

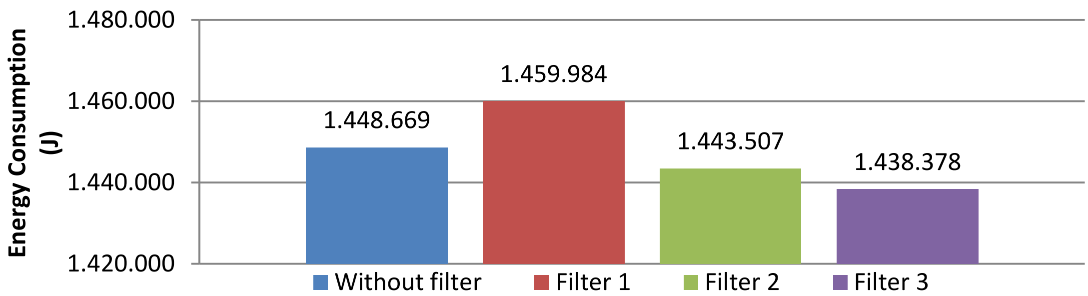

Figure 19. Total energy consumption considering the period of 0-36,000s

During the regime of full operation, it can be observed a reduction in energy consumption of 2.4%, 3.7% and 4.7%, using the filters 1, 2 and 3, when considering the system without the filter (Figure 20). This is because the smaller the number of occurrences of refrigerant fluid migration the lower the energy expenditure by the compressor to perform the redistribution of refrigerant during the new system start up. As discussed by Coulter and Bullard (1995), fluid migration can also lead to heating of the evaporator and, during the compressor restart, the initial stages of operation are used to offset this increase in the temperature of the evaporator.

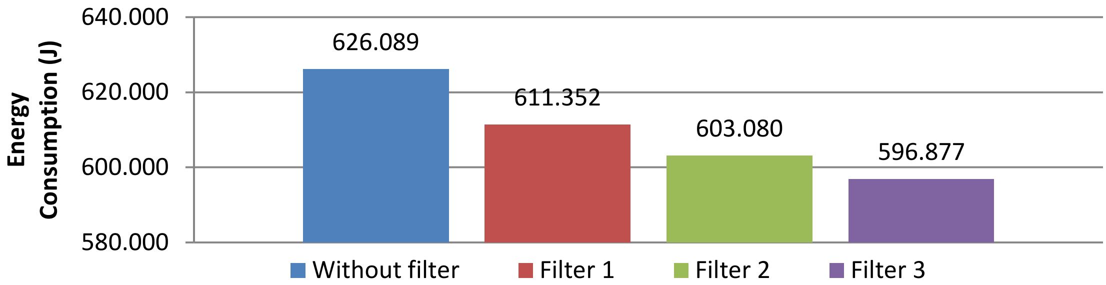

Figure 20 – Total energy consumption considering the period of 18,000-36,000s

In Figure 21 is presented the average power consumption. To calculate this parameter, it was considered only the last cycle of each test. In this cycle was despised the time in which the compressor was switched off. Then, the power curve was integrated using the trapezoids method. The value of this integral, in Joules, was divided by the operation time in the considered cycle, getting the average active power, in Watts.

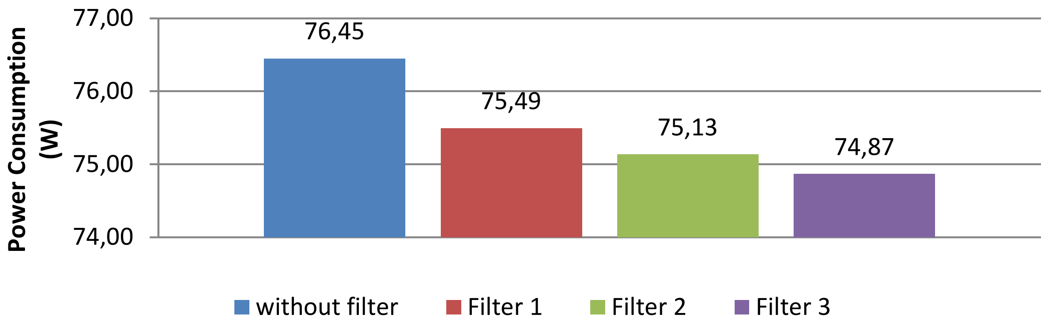

Figure 21. Average power consumption considering only the last operating cycle.

5. CONCLUSION

With this work it was demonstrated that the use of a filter in the compressor control circuit reduces the frequency of the on-off cycles. This procedure did not change significantly the refrigerator's internal temperatures. The maximum temperature variation was of 0.4°C on top of the refrigerator and of 1°C next to the evaporator. Subsequent studies are needed to verify if this temperature variation could compromise the conservation of foods stored inside the refrigerator.

Considering the steady-state period analyzed in this work (from 18,000 to 36,000s), after turning on the refrigerator at ambient conditions set forth in Table 1. It turns out that by using the filter, decreases the total time that the compressor is on and the frequency of the cycles was reduced, what reduced the effects of the refrigeration fluid migration and reduces the active power per cycle. With the sum of these factors, it was achieved a total energy saving of up to 4.7%, depending on the Tp value set in the filter transfer function.

6. ACKNOWLEDGEMENTS

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