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Optimized On-Off Controller For Energy Saving In A Household Refrigerator

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ABSTRACT

The domestic refrigerator is responsible for 30% of the average household electricity consumption in Brazil, and the power costs regarding a single refrigerator represents up to 5% of the Brazilian minimum wage. The capacity control method employed in most of these systems consists of a thermostat used to turn the compressor on and off to maintain the temperature between the desired levels. This method of capacity control is responsible for efficiency losses as a result of the start-up and shut-down transients. The duration and the number of on/off cycles directly influence the temperature profile inside the refrigerator and the system energetic efficiency. By adjusting the thermostat, the maximum and minimum temperature achieved during the system operation are changed, as well as the range between them. Having all that in mind, the aim of this study is to optimize the temperature range in a domestic refrigerator in order to make power consumption as low as possible while maintaining a given maximum temperature that cannot be exceeded in order to keep the food properly preserved. The refrigerator was modeled as a first order plus time delay system. A hysteretic relay test was used to estimate the system parameters. The system model was employed to develop mathematical relations to set the temperature amplitude inside the refrigerator, given a maximum temperature, in order to minimize the total energy consumption. The model presented indicated that, for the refrigerator studied in this work, the optimal amplitude should be set at approximately 7.5 °C, when the refrigerator is loaded with 40 water boxes. Experimental results showed that, using this temperature amplitude resulted in energy consumption 1.7% higher than the best measured value for the same load condition. The model also calculated 9.4°C as the optimal temperature amplitude for the empty refrigerator. With this amplitude, the empty refrigerator consumed the least energy when compared to other tested amplitudes.

1. INTRODUCTION

Household refrigerators are found in 96% of Brazilian residences (PROCEL, 2007) and in 99% of all North American residences (United States Census Bureau, 2010). The capacity control method employed in most of these systems consists of a relay that turns the compressor on and off in order to keep the temperature within the desired limits (Binneberg et. al, 2002). However, it is well know that this kind of capacity control method presents inherent losses that decrease the system efficiency.

Cyclic control in refrigerators causes fluid migration after the compressor shut-down. As the fluid migrates, it takes external heat inside the refrigerator chamber. This control method also imposes periodic temperature changes of thermal masses of components of the circuit, such as the compressor and the heat exchangers during the start-up of the compressor, which demands additional energy into the process (Coulter and Bullard, 1995). Both this phenomena undermine the system efficiency. If compressors were driven at variable speeds, energy savings of up to 30% could be achieved (Binneberg et. al, 2002).

Even though the on/off control method is usually less efficient, several authors have developed studies to make this kind of control as efficient as possible. Li et. al (2010) developed a method for optimizing the temperature bounds in refrigerated transport systems with a weighted cost function taking in account energy consumption and compressor wear. Deng et al. (2009) developed a simple approach to minimizing costs with air conditioning by minimizing the switching frequency and by maintaining acceptable temperature ranges for human comfort. Leva et. al (2008) presented a adaptive on/off control scheme by adding a linear filter with adaptive gains in the loop to limit the temperature amplitudes inside the refrigerator. Leva et. al. (2008) took as central issue in his article the fact that the load inside the refrigerator is not constant, which implies the need for an adaptive scheme, which was not presented by Li et al. (2010).

This work aims to present a simple adaptive control scheme, with includes a relay feedback identification approach, studied by Yu (1999) and Åström and Hägglund (1984). Based on the parameters identified, the optimal temperature range in a given point of the refrigerator will be determined. This temperature range will be set in the relay control and will be continuously adjusted in order to reduce the power consumption as much as possible. The resulting optimal range is a trade-off between losses due to the cyclic operation of the refrigerator, which are dominant in high frequency cycles, and losses due to the decrease in the efficiency of the thermal machine and the increase of heat transfer from the room, caused by temperatures inside the refrigerator at ranges excessively below the set point, which are dominant in low frequency cycles.

It is important to point out that the constraint to the optimization is the maximum temperature at the controlled point. Microbiological growth can only occur above a certain temperature level (regarding refrigerated temperatures only), therefore if a certain temperature level is not exceeded, the food is protected from microbiological attack. Furthermore the growth rate of most bacterial and fungal species is mostly determined by the highest temperature to which they are frequently subject (Jay, 1992). It is important point out that the model only takes in account temperature in one spot of the refrigerator, therefore, only there; the temperature will reach the prescribed levels. To guarantee food safety in the entire cavity, a model is needed to relate temperatures between the controlled point and the remaining of the refrigerator.

2. METHODOLOGY

2.1 Test Bench

In order to test the identification method and validate the control scheme for power saving, it was used a budget household refrigerator with total capacity of 239 liters. The refrigerator uses a capillary tube as expansion device and it is fitted with a commercial hermetically sealed compressor. The specifications of the compressor are: nominal power 75W (±5%); cooling capacity 96.7W (±5%); efficiency 1.29W/W (-9.04%/+10.5%); operating voltage range 100-140V; nominal current 0.96A (±5%); operating frequency 60Hz. The compressor has a slip-phase single-phase motor. A secondary winding is used for starting it. When a PTC-type relay reaches a predetermined temperature, the secondary winding is disconnected and the primary winding turns the motor.

The temperature data collected by França (2015) was measured by a LM335 temperature sensor with less than 1K of error guaranteed by the manufacturer. The sensor was installed on the freezer portion of the refrigerator. Room temperature was measured by T-type thermocouples and collected by a data acquisition system and sent to a computer. In this study, temperature data (both room temperature and internal temperature) was measured by DS18B20 temperature sensors with error of less than 0.5K guaranteed by the manufacturer, data was collected by an 8 bit microcontroller, which was also used to control the compressor of the refrigerator. In this study, temperature was measured in only one point inside the refrigerator, inside the freezer compartment, on the center of the lower wall.

A commercial power meter was employed by França (2015) to collect all electrical data; including real power, reactive power, power factor, current and voltage. In all other next tests, the 8 bit microcontroller was employed to collect all electrical data, including real power, reactive power, power factor, current and voltage. Such measurements were made using the scheme proposed by OpenEnergyMonitor (2014). The data collection circuit was calibrated with the same commercial power meter used by França (2015).

In order to change the load inside the refrigerator, water-filled boxes were inserted inside the refrigerator. No boxes were placed inside the freezer chamber, in order to avoid the freezing of the water. The boxes were placed as evenly spaced as possible.

2.2 System Identification

To choose the best method for the system identification, data previously collected by França (2015) on the same test bench was analyzed. Figure 1 shows the results of a test performed starting at room temperature. Such data shows the general behavior of the system. Figure 1 shows the full test. It is possible to see the initial temperature drop as the tests begins (shown in detail in Figure 3) and an abnormal increase in temperature as the door is opened to remove boxes. Figure 2 shows in details the cyclic operation of the refrigerator, which causes the temperature to vary in the manner shown. The refrigerator was initially loaded with 50 boxes of water. Following 20 boxes were removed and finally 20 more boxes were removed. The temperate limits for turning on and off the compressor were set as -7.2°C and -11.2°C. Room temperature oscillated during the test from 20°C to 21°C.

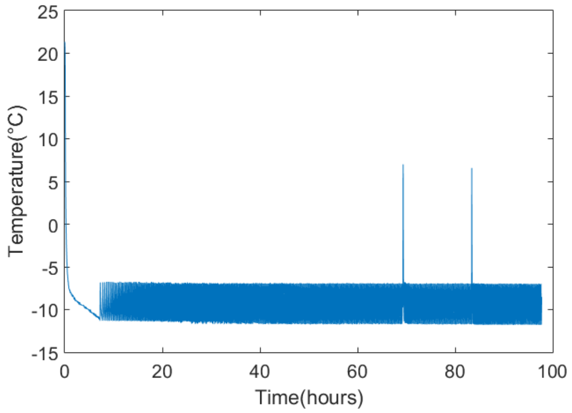


Figure 1: Refrigerator test with 50, 30 and 10 boxes of water

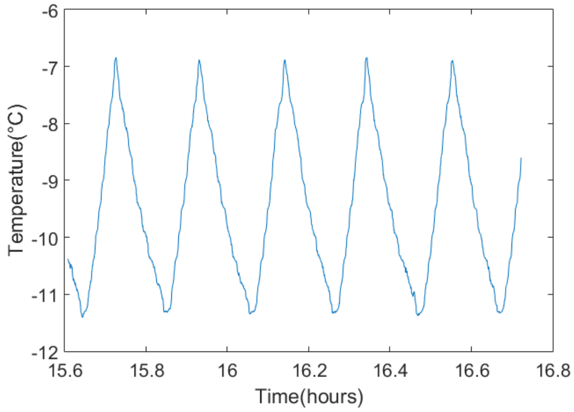


Figure 2: Refrigerator cycling operation

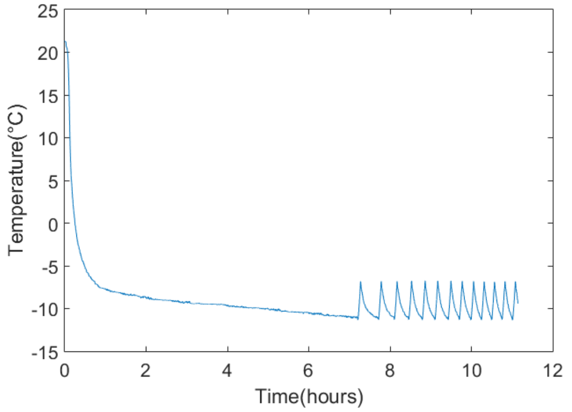


Figure 3: Refrigerator cycling operation start-up

In order to identify the system dynamics, it was used a relay feedback test. This test can be performed during the normal operation of the refrigerator, so it could be performed from data previously collected and do not demand any increase of temperature above the level required for food safety. Additionally, according to Yu (1999), this method is faster that the step response method for system identification when the time delay (D) is smaller than 0.28 times the system time constant (τ). Furthermore, as it can be seen in Figure 2, the measured temperature is very straight shaped, which is typical of systems of very low D/τ rates, therefore a relay identification method is recommended by Yu (1999).

The observation of Figure 2 promptly reveals that the system has sharp corners in the output, which, according to Yu (1999) is typical of first order systems. It can also be seen that the temperature limits go beyond the limits set by the hysteresis relay. Therefore it is reasonable to model the system as a first order plus dead time system (FOPDT). The general form of a FOPDT transfer function is given in Equation 1, where K represents the steady state gain.

$$G(s) = \frac{K}{\tau s + 1} e^{-Ds} \tag{1}$$

It is important to stress that for a thermal system, the output is usually defined as the difference between the controlled temperature and room temperature. The absolute value of this difference will be considered as the output in order to obtain a typical positive gain FOPDT. The output is herein referred to as cooling level (col).

The formulation proposed by Åström and Hägglund (1984) and the formulation proposed by Yu (1999) were employed to perform the system identification. It was also utilized a new formulation elaborated by the authors. To evaluate the performance of these tree methodologies, the test transfer function presented in Equation (2) was utilized. The values of K, D and τ were chosen based on preliminary analysis of the data shown in Figures 1 and 2.

$$G(s) = \frac{50}{1000s + 1} e^{-30s} \tag{2}$$

The system identification by a relay test is based on several parameters as shown schematically in Figure 4.

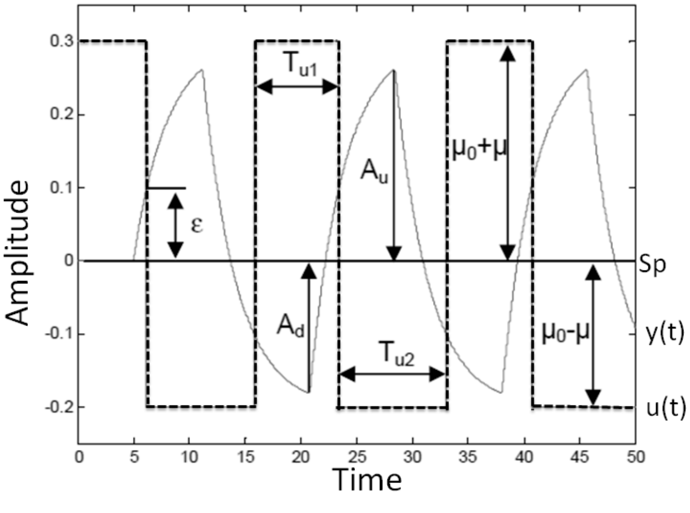


Figure 4: Parameters obtained from relay feedback teste of stable processes - Prokop (2010). Red line: System input; blue line: system output

As usual, y(t) is the time domain response of the system, which is this case, is the same as col, and u(t) is the time domain input to the system. The parameter A_u represents the positive response amplitude and A_d represents the negative response amplitude. The response amplitude, the sum of A_u and A_d, is A. T_{u1} is the higher input period while T_{u2} is the lower input period. T_u represents the period of the oscillation. ε is the relay hysteresis, μ_0 is the relay reference value and μ is the relay amplitude. The set point (Sp) at which the test was performed is 0. This is so because both of the formulations proposed by Åström and Hägglund (1984) and Yu (1999) aim at a test with a set point value (Sp) of 0. Yu (1999) mentions that a small deviation of the Sp from 0 could be beneficial to the test, but none of the authors discuss the matter in detail.

Therefore, identification trough the manipulation of the time response equations of a FOPDT system model was also tested. The set of equations used in the system identification are shown in Table 1. The time response method is proposed by the authors.

Table 1: Equations for the system identification

<table>
<tr><td colspan="3">Åström and Hägglund (1984)</td></tr>
<tr><td>$K = \frac{\int_0^{\mathrm{Tu}} y(t)dt}{\int_0^{\mathrm{Tu}} u(t)dt}$ (3)</td><td>$\tau = \mathrm{T}_{\mathrm{u1}} \cdot \left(ln \frac{2 \cdot \mu \cdot e^{\Theta} + \mu_0 \cdot \mathrm{K} - \mu \cdot \mathrm{K} + \varepsilon}{\mu \cdot \mathrm{K} + \mu_0 \cdot \mathrm{K} - \varepsilon} \right)^{-1}$ (4)
$\Theta = ln \frac{(\mu_0 + \mu) \cdot \mathrm{K} - \varepsilon}{(\mu_0 + \mu) \cdot \mathrm{K} - \mathrm{A_u}}$ (5)</td><td>$D = \tau \cdot \Theta$ (6)</td></tr>
<tr><td colspan="3">Yu (1999)</td></tr>
<tr><td>$K = \frac{\int_0^{\mathrm{Tu}} y(t)dt}{\int_0^{\mathrm{Tu}} u(t)dt}$ (3)</td><td>$\tau = \frac{\mathrm{T_u}}{2\pi} \cdot \sqrt{\frac{(4\mu \cdot \mathrm{K})^2}{\left(\pi \cdot \frac{\mathrm{A}}{2}\right)^2 - \varepsilon^2} - 1}$ (7)</td><td>$D = \frac{\mathrm{T_u}}{2\pi} \cdot \left(\pi - \tan^{-1}\left(\frac{2\pi \cdot \tau}{\mathrm{T_u}} \right) \right)$ (8)</td></tr>
<tr><td colspan="3">Time Response Method</td></tr>
<tr><td>$K = \frac{\int_0^{\mathrm{Tu}} y(t)dt}{\int_0^{\mathrm{Tu}} u(t)dt}$ (3)</td><td>$\tau = \left(l\,n \left(\frac{\mathrm{K} - (\mathrm{Sp} - \mathrm{A_d})}{\mathrm{K} - (\mathrm{Sp} + \mathrm{A_u})} \right) + l\,n \left(\frac{Sp + A_u}{Sp - A_d} \right) \right)^{-1} \cdot \mathrm{T_u}$ (9)</td><td>$D = t_{rs} - t_{rc}$ (10)</td></tr>
</table>

Where t_{rs} is the time when the relay is switched on or off and t_{rc} is immediate afterwards time when a increasing temperate starts to decrease or an increasing temperature starts to decrease.

By observing Figure 3, it becomes clear that the system does not respond as a FOPDT from room temperature. But since the function presents corners, it is not a higher order system, but instead, a non linear system (Yu, 1999). As stated by Yu (1999), non linear systems may be modeled by linear systems in a narrow range of response. Alternatively, the author suggests that non linear systems may be modeled as a set of linear systems that will cover the full range of response. As the function is identified by a test performed in the same operation range of response and the proposed scheme of control performs frequent system identifications, the non linearity of the system is not an immediate concern.

2.3 Optimal On Off Control

The on/off control is the most used method of capacity control in domestic refrigerators. It is well know that this scheme of capacity control is inefficient due the losses related with fluid migration and the transients of start-up and shut-down of the compressor. The frequency of the on/off cycles influences the system energetic efficiency. High frequency cycles tend to waste energy during the compressor start-up, due to the inrush current and on the shut down due to fluid migration; while low frequency cycles introduce energy losses due to the increase in the heat transfer, as a result of increased convection and conduction, and the decrease in the system efficiency when lower temperatures are reached inside the refrigerator.

In order to quantify the energy loses caused by the compressor start-up, the steady-state power consumption and the start-up energy use were measured. It was also evaluated the time required to reach a power consumption numerically equal to the steady state power consumption (start up time - SUT). At this time, it was considered that the compressor reached the steady state. By subtracting the energy that the compressor would consume in steady state during the period of the start up from the energy consumed by the compressor to start-up, it was obtained the start-up energy (SUE). By dividing SUE by the steady-state power consumption, the result is the equivalent extra steady state time (ET) required for the compressor to consume the same extra power consumed by the start-up process. This way, the extra power consumed during start up can be treated as the refrigerator working an extra time on steady state consuming power, but not generating refrigeration.

In the test shown in Figure 1, França (2015) also measured the power consumption of the refrigerator. By analyzing that data and calculating the value of ET for each cycle, in the manner described above, it is possible to possible to evaluate how ET varies from cycle to cycle. The value of ET for each cycle is show in Figure 5.

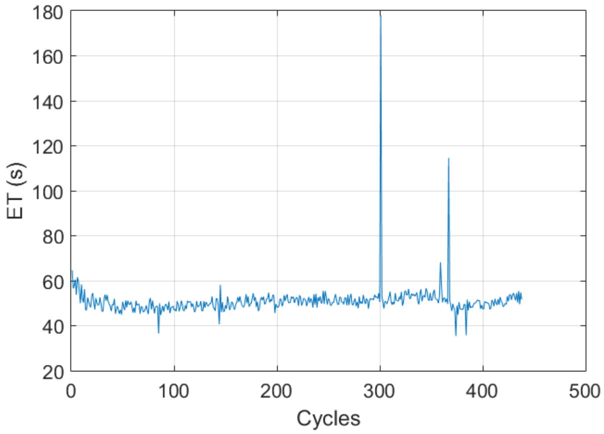


Figure 5: Refrigerator test with 50, 30 and 10 boxes of water - ET

It is clear that the value of ET remains stable within 5s maximum deviation, except during the first cycles of the compressor and during the first cycle immediately after the refrigerator is opened (the peaks approximately at cycle 300 and 370). In this study it was considered that ET is independent from the cycle number after the start of the test. With the concept of ET previously defined, the minimization of power consumption can be achieved by minimizing the relation between the on period of the cycle (ONT) plus ET and the full time cycle, which is the sum of ONT and the off period of the cycle (OFFT).

The time domain response of the system is given by Equation 11, while the input is 1 and by Equation 12, while the input is zero. TS is defined as the difference between room temperature and the maximum allowed temperature measured. TA is defined as the temperature amplitude inside the refrigerator. By setting the bounds of y(t) as TS and TS plus TA and applying them to Equations 11 and 12, the values of ONT and OFFT may be rewritten as Equations 13 and 14. In Equation 15 ONT plus OFFT represents the length of a cycle, meanwhile, ONT plus ET represents the time during the cycle when the refrigerator consumes the steady state power required by the compressor. Therefore, PR represents the fraction of the power the refrigerator consumes when compared to a refrigerator whose compressor is permanently on.

In order to make power consumption as low as possible, the value of PR has be minimized, which is shown in Equation 16. By numerically solving equation 16 for TA, the optimum value for temperature amplitude inside the refrigerator is obtained.

$$y(t) = K\left(1 - e^{\frac{-t}{\tau}}\right)\ ;\ u(t) = 1 \tag{11}$$

$$y(t) = K\left(e^{\frac{-t}{\tau}}\right)\ ;u(t) = 0 \tag{12}$$

$$\text{ONT} = ln\left(\frac{K - TS}{K - (TS + TA)}\right) \cdot \tau \tag{13}$$

$$\text{OFFT} = ln\left(\frac{\text{TS} + \text{TA}}{\text{TS}}\right) \cdot \tau \tag{14}$$

$$\text{PR} = \frac{\text{ONT} + \text{ET}}{\text{ONT} + \text{OFFT}} \tag{15}$$

$$\frac{d\text{PR}}{d\text{TA}} = 0 \tag{16}$$

Figure 6 shows the value of PR for different values of TA (based on Equation 15). In order to present this graph, a TS value of 35 and a room temperature of 25 °C were adopted. It represents a temperature of -10 °C inside the refrigerator, which is a typical value for preserving food (USDA, 2013). An ET value of 60 was adopted based on Figure 5. All other constants were taken from Equation 2.

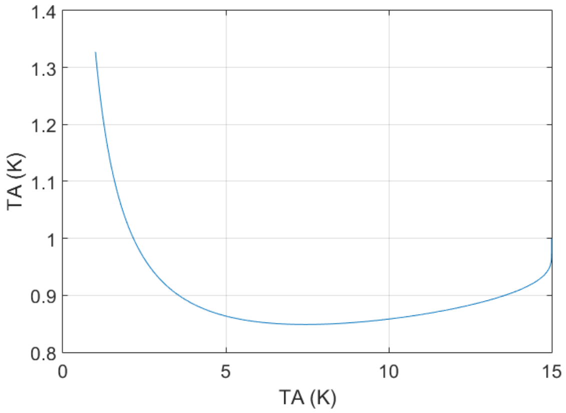


Figure 6: Example of a TAxPR curve

PR values for the TA values below 1 were not plotted. As TA goes to 0, PR goes to infinite as the cycle will have a period of 0. This scenario has no physical meaning as the model takes as a premise that the compressor will reach steady state before the end of the on portion of the cycle, which does not occur in very short cycles, not even as a rough approximation. The maximum possible value of TA, for the example shown is Figure 6 is 15. This value represents a 50 K temperature difference from room temperature (TS=35), which is the FOPTD system gain. The system will thus asymptotically reach that cooling level without ever turning off the compressor; therefore PR has a value of 1 for this condition. Optimal value of TA for this example is 7.44K.

3. RESULTS

3.1 System Identification

In order to test the equations for the identification of the system, tests were run with the simulated FOPDT model given in Equation 2. The parameters shown in Table 2 were used in the test. Those aim to simulate the approximate working conditions of a refrigerator. The results are shown in Table 3.

Table 2: Parameters used to test identification equations

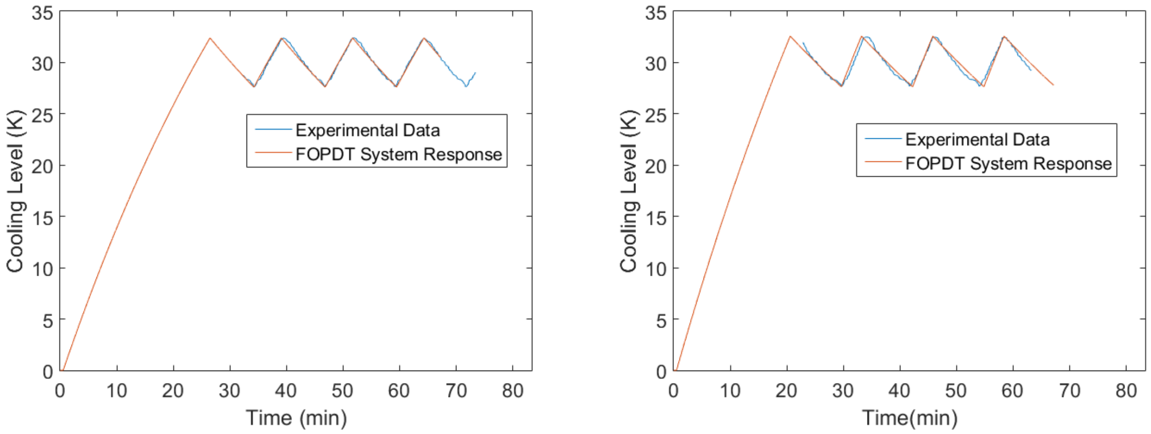
μ_0	0,5
μ	0,5
Sp	30
ε	4

Table 3: Identified FOPDT model parameters

Set of Equations	Parameter	Value
Real Values	Gain (K)	50
	Time Constant (τ)	1000
	Time Delay (D)	30
Åström and Hägglund (1984)	Gain (K)	50,0
	Time Constant (τ)	2750
	Time Delay (D)	28,7
Yu (1999)	Gain (K)	50,0
	Time Constant (τ)	1696
	Time Delay (D)	204
Proposed Method	Gain (K)	50,0
	Time Constant (τ)	1000
	Time Delay (D)	30,0

Table 3 shows that the equations by Åström and Hägglund (1984) and Yu (1999), do not estimate very well τ when the Sp is very distant from zero. The equations by Yu (1999) do not correctly estimate the value of D either. Therefore, in this study, it was adopted Equation 3 to indentify K, Equation 9 to indentify τ (based on the time response) and Equation 6 (Åström and Hägglund, 1984) to indentify D. Although Equation 6 was not as precise as Equation 10 in the test above to estimate D, the method by Åström and Hägglund (1984) is more widely discussed in the literature and is precise enough for this study, therefore it will be adopted.

To further verify the accuracy of the selected methods, models were obtained from data shown in Figure 1. The models were then run with the same settings of the actual refrigerator, and the results are presented in Figures 7.a and 7.b. The results show that models indentified reproduce with good accuracy the behavior of the actual refrigerator in cycling condition.



Figures 7.a and 7.b: Indentified systems vs. experimental data - 50 (a) and 10 (b) boxes of water

3.2 Power consumption

In order to evaluate the power consumption with the refrigerator operating with different temperature ranges the following scheme was adopted: first, the refrigerator began operating with arbitrary temperature amplitude (TA) for a given value of TS. During this operation, the system parameters, as well was the value of ET, were collected. The ideal temperature amplitude was then calculated. Finally, the refrigerator was set to operate with different values of TA and the power consumption was measured. Room temperature was kept constant during the whole test. The first test was performed with an empty refrigerator, while the second test was performed with 40 water boxes inside it. The results for the test parameters are shown in Table 4.

Table 4: Test parameters

Parameter \Test	Test 1	Test 2
Water boxes inside the refrigerator	0	40
Room temperature	22 ºC	22 ºC
Maximum set temperature inside the refrigerator	-7 ºC	-7 ºC
Initial temperature amplitude (TA)	7 ºC	7 ºC
Identified gain (K)	110.8	62.3
Identified time constant (τ)	1897.6 s	916.4 s
Identified time delay (D)	28.2 s	11.2 s
ET	32.4 s	26.48 s
Optimal temperature amplitude (TA)	9.4 ºC	7.5 ºC

The average power consumption for each test for each temperature amplitude tested, as well as the theoretical power consumption calculated by Equation 15 is shown in Figure 8 for test 1 and in Figure 9 for test 2.

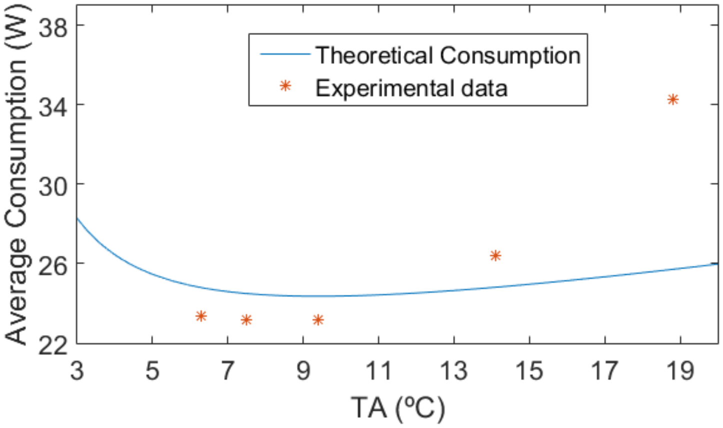


Figure 8: Average power consumption - Empty refrigerator

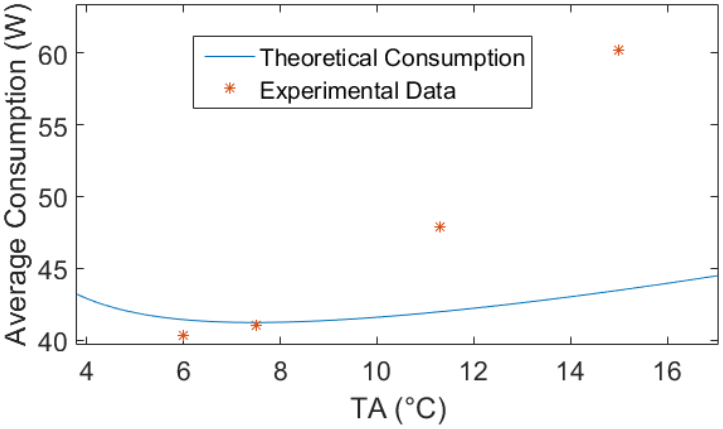


Figure 9: Average power consumption - 40 boxes

In Figure 8, the calculated optimal TA value was 9.4 ºC. Results showed that this temperature amplitude actually provided the best average power consumption for the empty refrigerator, even though lower values of TA presented similar energy consumption values. The TA value of 9.4 ºC provided an energy saving of 48% when compared to a TA value of 18.8 ºC and an energy saving of 1% when compared to a TA value of 6.3 ºC. In Figure 9 it was observed an optimal calculated TA value of 7.5 ºC. Data from testing showed similar, but lower, average power consumption for lower values of TA. In Figure 9, the calculated value of TA resulted in experimental power consumption 1.7% above the best measured value. Although the calculated optimal value of TA did not provide the best power consumption, the power consumption with this value of TA is 47% better that with a TA value of 15 ºC; and 17% better than with a TA value of 11.3 ºC. It is also important to point out that the optimal value of TA, both measured and predicted, varied with as water boxes were placed inside the refrigerator which confirms that an adaptive control scheme, such as the scheme provided, provides advantages regarding power consumption in refrigeration systems.

As expected, the model did not present a satisfactory prediction of the average power consumption for higher values of TA. This is so because heat transfer through natural convection tends to increase more than linearly as temperature differences increase. This phenomenon caused the system to behave much worse than expected as TA increased. For the same reason, the system proved itself to be less power consuming than predicted while operating with lower values of TA. The exact prediction of power consumption at different values of TA is not important to the control scheme itself, as the goal is only minimize the power consumption. In order to predict the complete behavior of the system, a non linear model is required as well as a time dependent formulation for ET. This approach is much more complex that the one presented. The non linear system identification would require multiple tests (Yu, 1999) and they could not be performed during the regular operation of the refrigerator. Additionally the computational effort to calculate and predict the system behavior would not allow the optimization to be performed in a simple and cheap 8 bit microcontroller.

It was not possible to measure the power consumption for the system with lower TA values as it would require two start-ups of the compressor with not enough time between them for the PTC-relay to cool down and allow for the second start-up. For testing a wider range of TA values, regarding their respective power consumption, another start-up method would be required for the compressor.

4. CONCLUSION

The proposed scheme was successful to calculate an optimal value for the temperature amplitude (TA) inside of a refrigerator in order to save energy. For the empty refrigerator, the model calculated the most power saving temperature amplitude among the measured ones. The calculated 9.4ºC amplitude was 1% more efficient than a 6.3ºC amplitude and 48% more efficient than a 19ºC amplitude. For the refrigerator filled with 40 boxes of water, the calculated TA of 7.5 ºC provided power consumption 1.7% higher than the lowest recorded value, but it was still 47% more efficient than a 15 ºC amplitude. The presented scheme may be used to estimate optimal output amplitude values for any system that could be treated as a FOPDT with activation energy. The system non linearity did not allow the model to predict the system behavior trough a wide range of TA values. This was caused primarily by the fact that natural convection in a highly non linear phenomenon that increases abruptly as temperature differences increase. This control scheme could be improved by the adoption of a non linear system model and by a time dependent formulation of the activation energy of the compressor.

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