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ENERGY CONSUMPTION ANALYSIS OF A REFRIGERATOR-FREEZER EMPLOYING A SENSOR INSIDE A FLUID WITH HIGH THERMAL CAPACITY

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Abstract. *The refrigerator is an important household appliance due to its popularity and the significant participation in the domestic energy consumption. In most of domestic refrigerators, the temperature of the air inside is employed as parameter in the on/off controller. Though, since the air temperature response is generally faster than the response of the other items stored inside the refrigerator, some on/off cycles may be unnecessary. This can lead to an increase in the energy consumption and make the products to be stored in a temperature that is not suitable. In this work it is proposed a digital on/off controller with a physical filter in the form of a liquid of high thermal capacity to adjust the internal temperature of a domestic refrigerator. The temperature used as parameter to the control system was that of ethylene glycol, a fluid with higher thermal capacity than air, as an attempt to better represent the temperature of the items stored. Using the filter it was achieved a 30% reduction in the number of cycles while it was followed by a reduction in energy consumptions of 11.0% and 10.8% with the refrigerator empty and loaded, respectively.*

Keywords: *household refrigerator; on/off control; energy consumption; digital controller, temperature control*

1. INTRODUCTION

Energy efficiency in household appliances is a recurring subject. Among the most demanding household appliances, is the refrigerator-freezer. The refrigerator alone accounts for 32% residential electrical consumption in Brazil (BEN, 2014). That, and the fact that the refrigerator stays on all day long, motivates researches to improve its efficiency.

A recurring problem with refrigerator, research, is because the norms do not work well with the modern refrigerators, because they were made in a way to get better results using those norms. In this way, the energy results found in laboratory are not consistent with the real world (Bansal, 2003). Brown et al. (2013) tested the average temperature of 48 refrigerators under real household usage, however only 14 were functioning according to the label.

Even though it is known that the norms cannot fully simulate real conditions, it is expected that in experiments with door opening the energy consumption will increase. According to the National Consumers Affairs Center of Japan (NCAC), six refrigerators tested in the JIS C 9607 had 9.0-26.6% less energy consumption when tested with doors closed.

Saidur et al. (2001) studied the role of the room temperature, the position of the thermostat and the numbers of door openings and concluded that most relevant to energy consumption is the room temperature followed by the number of door openings. This study however was carried out in a situation where the outside temperature variated from 14°C to 32°C, which is by no means an usual thing, also he did not conducted tests with thermal loads.

Liu et al. (2004) performed an interesting study quantifying the hysteresis when the room temperature is drastically, changed. For changes of 15°C, the hysteresis can increase up to 2°C in the cabinet.

Considering that the main concern of the refrigerator is food refrigeration, the air temperature becomes a poor indicative for the food temperature, since whenever there is a door opening, good part of the air is recycled, and because of the thermal capacity of the air compared to the food, large variation in air temperature only mean few degrees on the actual food temperature. Taking in to account that the food response to heat is slower than the air, it is possible to reduce the energy consumption of door openings by submerging the thermostat in fluid with thermodynamic behavior similar to the foods inside the cabinet. The reason for the reduction of energy consumption is that because the fluid with higher thermal capacity needs more heat to both chill and warm, considering the same space of time and knowing that the compressor actuates always at the same velocity, the number of on/off cycles when using the sensor submerged will reduce. Reducing the frequency of on/off cycles reduce the energy consumption because every time the compressor is turned on, the inrush current elevates the consume, and there is a work to redistribute the refrigerant fluid that returns to the evaporator from the capillary tube during the off cycle, (Bullard and Coulter,1995).

In this work, the thermostat was replaced for a digital controlling unit, and the thermal information came from a digital sensor submerged in ethylene glycol.

2. EXPERIMENTAL APARATTUS

The experimental test bench consists of a CONSUL refrigerator-freezer model CRC2EEBAA. The volume according to the manufacturer is 280 liters. The compressor is hermetic, monophasic and operates on a voltage of 127V (±10%) and 60Hz. The rated power for the compressor is 75W (± 5%). The refrigerant fluid is R134-a.

A test-tube of 15 ml filled with ethylene glycol was fixed between the top grid and the freezer.

To measure the temperature, two different systems were used. The first one is composed of six thermocouples T-type connected to a data acquisition system. This system consists of a chassis model NI cDAQ NI-9178, in which was connected four modules NI N9211. It was developed a LabView routine, employed for the measurement automation, processing and storage of data. The sample rate used was of 5s.

The thermocouples were used to monitor the temperature at the outside air, the lower grid, the top grid, the ethylene glycol, the air outside the ethylene-glycol tube and the air at the middle of the freezer

The second measuring system consists of a digital sensor DS18B20, with 12bits of resolution. This sensor was placed inside the ethylene-glycol tube and outside the ethylene-glycol tube according to the test.

Figure 1 shows two tests configuration. One with the refrigerator empty and the other with the refrigerator loaded. The digital sensor can be seen at inside test-tube in one configuration, and at outside on the other.

Figure 1, Thermal sensor in different test configurations

To measure the electrical data, a multimeter KRON, model Mult-K Plus was used. A transformer was used to reduce the current to a third of the value since the inrush current exceeds the maximum value supported by the KRON. The electrical data recorded were voltage, current, power factor and both the active and reactive powers. The communication with the hardware was made through USB connection.

The control unit consisted of a TIVA – C digital board. This digital board commands the compressor on/off based on the temperature provided by the DS18B20 sensor.

All tests were performed in a laboratory with controlled temperature of 20°C (±0.5°C).

3. METHODOLOGY

The objective of this work is to evaluate the energy consumption impact when replacing the conventional thermostat of the refrigerator by a digital board and a digital sensor immersed in ethylene glycol. The control algorithm employed was the on/off.

The temperature values of 4°C and 2.5°C were chosen to be used as the superior and inferior limits of the on/off controller. Those values were chosen trying to minimize the numbers of cycles while keeping the food at a suitable temperature. Brown et al. (2013) discusses the storage life of various food (including various fishes and fruits) according to the temperature and concludes that food life increases exponentially when it is stored in temperatures lower than 5°C, while the maximum life depends on the food.

Four tests were conducted in order to evaluate the system performance. These tests consisted basically of measuring the temperature and electrical parameters of the refrigerator. No door- opening were allowed.

Two tests were conducted with the digital sensor in the air. One of them was performed with the refrigerator empty and the other one was executed with 11 liters of water inside. The tests were recorded for 12 hours in quasi- permanent state. The other two tests were performed the same way, but employing the digital sensor submerged in the ethylene glycol. Both were recorded for 12h.

In all the tests the digital controller was employed. For each test the following parameters of interest were shown: average maximum and minimum temperature, time spent with compressor on and off per cycle, number of cycles and energy consume.

4. RESULTS

Figures 2,3,4 and 5 shows the results for the four tests. These tests are presented in the following order: refrigerator empty – sensor in the air, refrigerator loaded – sensor in the air, refrigerator empty – sensor in the ethylene glycol, refrigerator loaded – sensor in the ethylene glycol. It can be seen in the figures that the number of cycles is changing, and along with them the various time constants and also energy consume. In the Tab. 1 is presented a summary of these data.

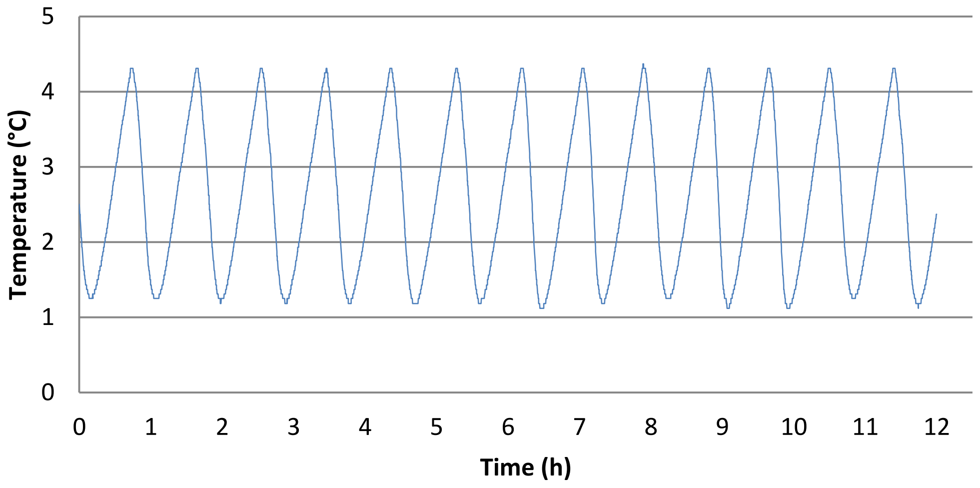

Figure 2, Temperature versus time for the empty refrigerator with sensor in air (Test 1)

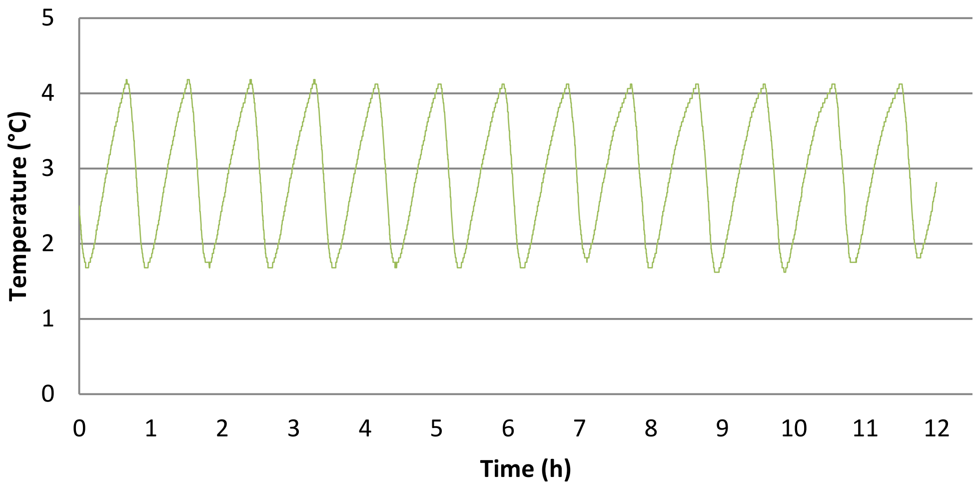

Figure 3, Temperature versus time for the loaded refrigerator with the sensor in air (Test 2)

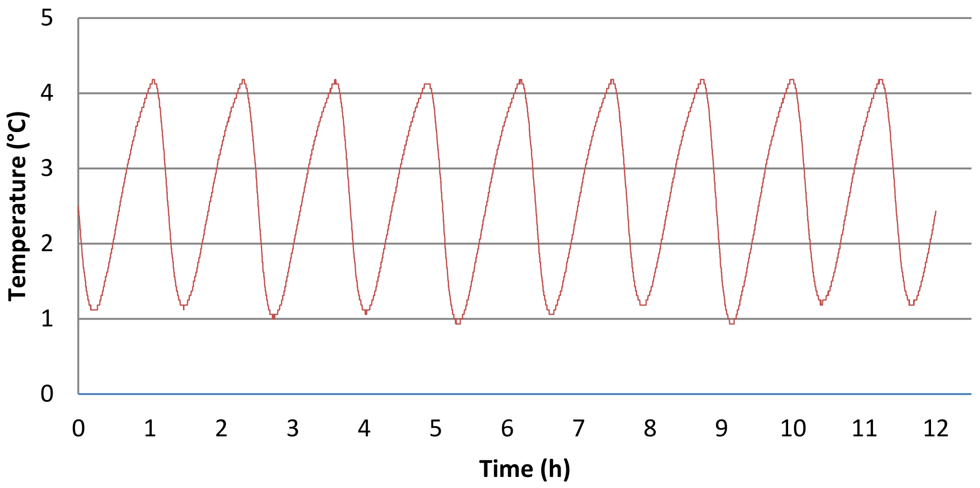

Figure 4, Temperature versus time for the empty refrigerator with the sensor in the ethylene glycol (Test 3)

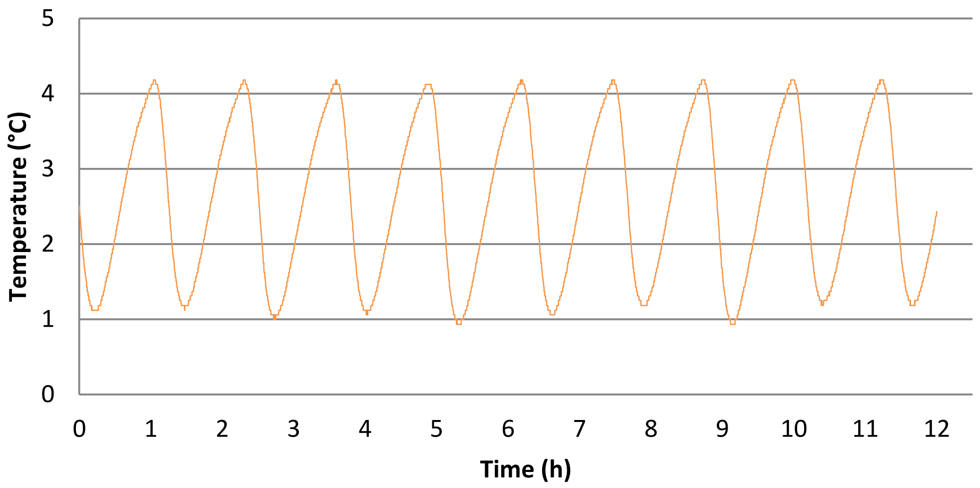

Figure 5, Temperature versus time for loaded refrigerator with the sensor in the ethylene glycol (Test 4)

Table 1, Experimental parameters for the tests

	Number of Cycles	Energy Consume (kWh)	On Time (s)	Off Time (s)	Average Cycle Time (s)	On Time per cycle (s)	Off Time per cycle (s)	Max. Temp. (°C)	Min. Temp. (°C)
Test 1	13	0.23480	10844	32355	3323	834	2489	4.3	1.2
Test 2	13	0.22987	10674	32552	3323	821	2502	4.1	1.7
Test 3	9	0.20885	9910	33289	4800	1101	3698	4.2	1.1
Test 4	9	0.20507	9913	33286	4800	1101	3698	4.2	1.1

According to Tab.1, the number of cycles for the tests with the sensor immersed in ethylene glycol (Test 3 and Test 4) were lower than the tests in which the controller used the temperature of the air. That is consistent, since the thermal capacity of the ethylene glycol is many times higher than the air. That means that for the same heat gain or loss, the fluid will experiment a fewer variation in temperature.

With the usage of the sensor immersed in the ethylene glycol, it was verified that the On Time reduced. This reduction means that the compressor is turned on for less time. Comparing Test 1 with Test 3, it was obtained a reduction of 8.6% on total on time, and comparing Test 2 with Test 4, it was obtained a reduction of 7.1%.

Using the sensor immersed in ethylene glycol proved to reduce the energy consumption. Comparing Test 1 with Test 3, the cases in which the refrigerator is empty, an energy consumption reduction of 11.0% was achieved. Also, comparing Test 2 and Test 4 an energy consumption reduction of 10.8% was achieved. Those reductions in energy consumption were consistent with both the reduction of the time the compressor stayed on, and also because of the reduction of the number of cycles, which diminishes the work spent in reorganizing the refrigerant fluid for each time the compressor would turn on.

Considering the temperature of 2.5°C was the inferior temperature for the on/off controller, the minimum temperature achieved in all tests presented a great overshoot and needs improvements. It was used as overshoot the difference between 2.5°C and the minimum temperature. The average overshoot for all tests is 1.2°C. A viable alternative is to use a variable velocity compressor, which along with the reduction of the overshoot can provide a great reduction in energy consumption. (Schwarz, 2001)

Figure 6 present a comparison during two cycles of the tests 1 – 4. In this figure it is clear the different temperature profile observed in each test. The temperature curve for the test with the sensor in ethylene glycol with the refrigerator loaded is being overlapped by the temperature curve for the test with the sensor in ethylene glycol with the refrigerator empty. This happens because in quasi-permanent state, the response is almost the same as evidenced in Tab. 1.

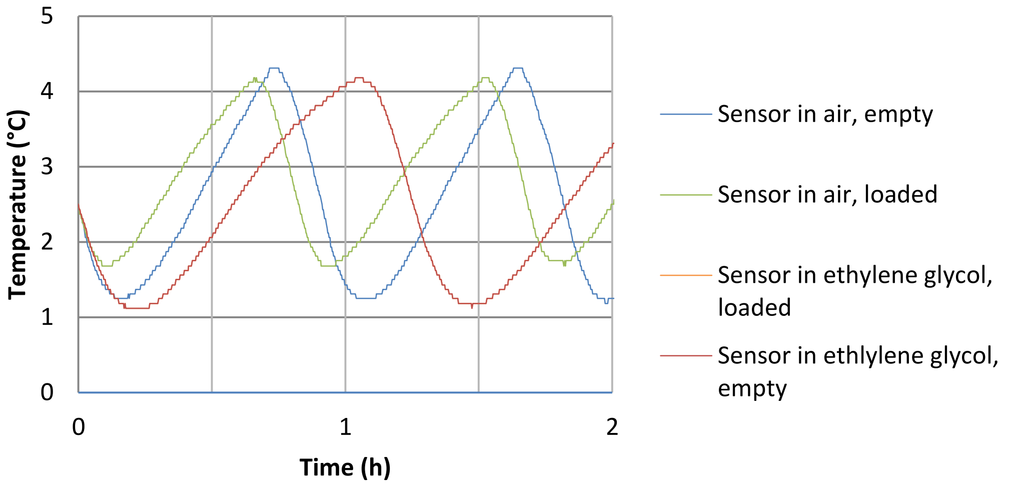

Figure 6, Two hours zoom temperature versus time

Figure 6 also serves to show the key point of this work. The fact that the temperature responses for the Test 3 and Test 4, implies that using the ethylene glycol to control the temperature improve the capability of the system of rejecting thermal disturbances, as it can be seen that a thermal load had almost no impact in the quasi-equilibrium state. Test 1 and Test 2 were conducted with the sensor in air, and had differences especially in the maximum and minimum temperature.

5. CONCLUSIONS

In this work it was shown that by substituting the thermostat for a digital controller unit using the temperature of a fluid of higher thermal capacity is an efficient way to make better temperature control and also reduce energy consumption.

The reduction in energy consumption when comparing the test of the sensor in air and the sensor in ethylene glycol, both cases with the refrigerator empty, was of 11.0%. The reduction in energy consumption when comparing the test of the sensor in air and the sensor in ethylene glycol, both cases with the refrigerator loaded was of 10.8%. That is due to reduction in both number of cycles and time spent with compressor working.

Also, in terms of temperature control, when the sensor is submerged in the ethylene glycol, it is much less subject to temperature fluctuations which help in real operation conditions.

Although the temperature control did improve, the overshoot is high, 1.2°C, which can be prejudicial to some stricter food conservation, and consume more energy. That motivates the usage of variable velocity compressor, which reduces the overshoot and energy consumption.

While no door-openings tests were conducted, the tendency of reducing the numbers of cycles should guarantee the reduction in energy consumption and a better temperature control, avoiding small disturbances such as adding or removing a thermal load.

Subsequent works in this area should be performed with door-opening tests and varying thermal loads, to better understand the impact of these disturbances in the system energy consumption, when the proposed methodology is employed.

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7. RESPONSIBILITY NOTICE