EXPERIMENTAL STUDY OF THE OPERATIVE CONDITIONS OF DOMESTIC REFRIGERATORS IN THE STUDENT COMMUNITY OF THE UNIVERSITY OF BEIRA INTERIOR

Diogo Galvão[1], Pedro D. Gaspar[1] *, Pedro D. Silva[1] and Luís C. Pires[1]

1: University of Beira Interior, Faculty of Engineering, Department of Electromechanical Engineering, Calçada do Lameiro, 6200-001 Covilhã, Portugal
e-mail: dgalvao0@gmail.com; dinis@ubi.pt; dinho@ubi.pt, pires@ubi.pt; web: http://www.ubi.pt

Abstract: *The temperature control of domestic refrigerators is crucial to ensure food safety and quality and as a means to reduce food waste. Several studies related to the temperature control of these appliances have been published over the past 15 years. In Portugal, although there are some studies that refer the food* storage *temperature in refrigerators, there are no studies that on to this influence of this parameter on the food safety. The current refrigerators include compressors with lower power and the appliances are better insulated ensuring a better thermal performance with less energy consumption. However, these outcomes depend on the installation conditions and equipment use. This experimental study is related to the analysis of the operative conditions of the refrigerators of the student community of the University of Beira Interior (Covilhã, Portugal). A test sample of 51 equipments was instrumented with temperature dataloggers, distributed by students who (1) live alone; (2) with their parents; or in conjunction (3) with other students. The test sample appliances have, on average, an electrical power of 126 W and an inner volume of 205 liters. It was found that the average temperature of products* storage *is 5.5 ºC, just above the food safety threshold. It was determined that the* storage *air temperature in the appliance increases with the number of people who uses it.*

Keywords: Domestic refrigerator, Experimental study, Operative conditions, Students households, Food safety.

1. **INTRODUCTION**

Nowadays the refrigerator is a common household appliance, being few the households in developed countries that do not have a refrigerator to keep cold the perishable food products [1]. The temperature control of food products is extremely important because the conservation by cold reduces the reproduction rate and the action of microorganisms and enzymes. The proper range of the cold storage air temperature is 0 °C to 5 °C [2]. In this way, the risks to the public health are reduced. However, evidence has shown that 70% of cases of food poisoning are originated from the domestic environment, due to inappropriate storage conditions that lead to pathogens growth [3]. Several studies on the thermal performance of domestic refrigerators have been published over the past 15 years [1-3]. The results of experimental studies related to the storage temperature monitoring are quite similar, ranging the global average temperature of the air between 2 °C and 6.5 ºC. The average values of maximum temperatures vary between 7.5 ºC and 20.7 ºC, while the average values of minimum temperatures vary between -7.9 ºC and 3.3 ° C. Through the analysis of the results of these studies, Peck *et al.* [4] found that 61.2% of the refrigerators around the world operate at temperatures above 5 °C [1-3]. The most recent study in order to study the thermal performance of domestic refrigerators was performed in the UK by Evans *et al.* [3].

This experimental study of monitoring the air temperature in domestic refrigerators was performed in equipment located in the households of the student community of the University of Beira Interior (UBI), Covilhã (Portugal). The temperature measurements were performed during 8 days with 1-minute acquisition time using a datalogger. The results show that the average values of the storage temperature ranges from -1.8 ºC to 11.9 ºC. The overall average temperature of the test sample was 5.53 ºC, where 60.8% of the appliances operate with an average temperature above 5 °C. In addition to the results of the thermal performance of refrigerators in a community not studied so far, this study aim to increase the awareness about best practices for increasing the food safety of perishables food products kept in domestic refrigerators as well as reducing the food waste. Additionally, the study compares the experimental results with those obtained in studies concerning the air temperature monitoring in refrigerators conducted in other countries.

2. MATERIALS AND METHODS

2.1. Test sample

The student community of UBI, for the school year of 2014-2015, was composed by 6014 students (UBI's Quality Office, 2014). A value of 201 students for test sample for the existing population is obtained assuming a confidence level of 85% and a confidence interval (margin of error) of 5% determined by Equation 1 [5]. Considering the data collected throughout this study, it is concluded that in each household inhabit approximately 3.8 students. Thus, it can be assumed that on average four students inhabit in each household. Assuming this condition, the optimal sample of equipment to be analyzed consists in 51 appliances. This sample value ensure the representability of the results and provides a reliable study.

$$n = \frac{N \cdot Z^2 \cdot p \cdot (1-p)}{Z^2 \cdot p \cdot (1-p) + e^2 \cdot (N-1)} \tag{1}$$

Where: n: ideal sample calculated; N: population in which the study is carried out, that is the number of elements in the research universe; Z: standard normal variable associated to the confidence level

(Z = 1.44 [5-6]); p: true probability of the event occur (probability of 50%, p = 50%); and e: margin of error.

2.2. Datalogger

Dataloggers of Lascar Electronics, model EL-USB-2-LCD+ were used for measurements. The dataloggers include temperature, relative humidity and dew point temperature sensors (see table 1).
The datalogger is a measuring device consisting of a battery, a sensor and a USB port to download the data stored in memory. The device operation is configured by software, such as the required time of measurements, values of temperature alarms (high and low), among others. The datalogger allows a wide range of configurations with regard to the desired time for measurements. The software also provides graphical visualization of the collected data, allowing overriding irrelevant data curves.
After setup, the datalogger is set to start acquiring data. Once activated, the device is placed in the environment where it will acquire the data. After the measuring time, the device may be removed to transfer the data to a computer for later analysis.

Table 1. Datalogger specifications.

Model		EL-USB-2-LCD+
Measurement		Temperature; Relative humidity; Dew point temp.
Measurement range		Temperature: -35ºC to 80ºC Relative Humidity (RH): 0% to 100%
Accuracy	Typical	±0.3ºC; ±2.0% RH
	Max.	±1.5ºC; ±4.0% RH
Maximum readings		16382

2.3. Data acquisition and processing

Data collection was conducted during 6 months from 2014 November 3rd to 2015 April 10th. However, the data acquisition was not continuous because during this period there were vacation weeks, examination periods, among other times that were inadequate or unsuitable for students. During these irregular conditions, the maximum time that the dataloggers stayed without measuring was 1 week. Under normal conditions, the dataloggers were no more than 24 hours without performing acquisitions. The procedure for data acquisition consisted on placing the datalogger in the middle height shelf of the refrigerator. In addition to the air temperature and relative humidity measurements, all the information and technical specifications of the appliances were collected in order to perform a reasonable comparison of results. The dataloggers remained acquiring data for a period of 8 days**, with a one-minute data acquisition rate.** Then, the measuring devices were removed from refrigerators and the acquired data was downloaded to a computer through the datalogger software. Thereafter, the collected data was processed (average, maximum, minimum and standard deviation values) for each appliance. It was necessary to delete some of the data measured by the sensor, particularly, the first data recorded was eliminated since the sensor does not start the measurement inside the refrigerator but outside at a higher temperature.

3. ANALYSIS AND DISCUSSION OF RESULTS

The analysis of the experimental results collected over a period of 8 days for each appliance allow to describe the operative conditions and the thermal performance of the refrigerators located in students'

households. Most of the temperature values are within the values at which the appliance must operate to ensure food safety. However, there are also some situations where the temperature values are outside the range for proper storage temperature.

3.1. Thermal operative conditions

The electrical power, P [W], and the capacity (volume), V [m^3], of a refrigerator are two of the most important features. These features were extracted from appliances specifications. The test sample devices have an average electrical power of 126 W (std dev = 59 W). The equipment with highest and lowest power have respectively 281 W and 56 W. The average cold storage volume is 205 liters (std dev = 79 liters). However, the inner volumes of test sample ranged from 133 liters to 427 liters. Figure 1 shows the linear correlation between V and P.

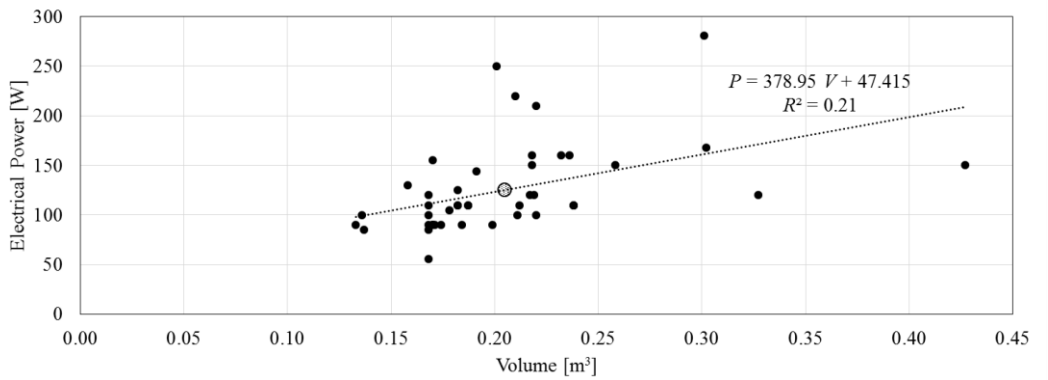

Figure 1. Linear correlation between volume and electrical power of the test sample.

The low value of the determination coefficient (R^2 = 0.21), despite de correlation type, indicates that there is not a strong relationship between cold storage volume and the electrical power. Thus, to enable a fair comparison between the test sample devices, the specific electrical power, p [W/m^3] was determined, which is shown in Figure 2 for the test sample. The different types of household sharing of students are differentiated in Figure 2 by colours. The "blue" cases are results of students who live alone, "green" cases are results of students who live with their family, i.e., native students from Covilhã; and "red" cases are results of students that share accommodation with other students.

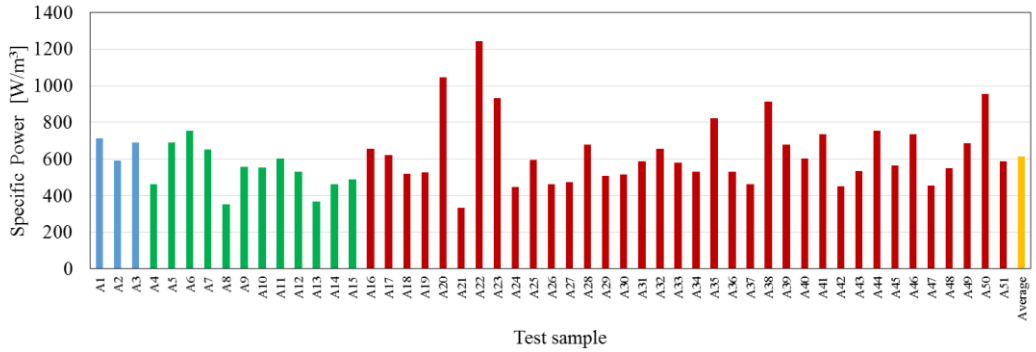

Figure 2. Specific electrical power of the test sample.

The specific electrical power of the sample equipment, extracted from the appliance specification, has an average value of 616 W/m^3 with a standard deviation of 241 W/m^3. The highest and lowest values of specific power are 1244 W/m^3 and 333 W/m^3, respectively (see Figure 2). Figure 3 shows the average, minimum and maximum values of the storage temperature of each appliance of the test sample. This figure also shows the overall average value and its minimum and maximum values. The colour bars sequence follows the same relationship as Figure 2. The overall average value of the storage temperature is 5.5 ºC. This value is 0.5 ºC above the operating limit range temperature for household refrigerators. The average operating temperature is over the suitable higher temperature limit in 66.6% of the case studies.

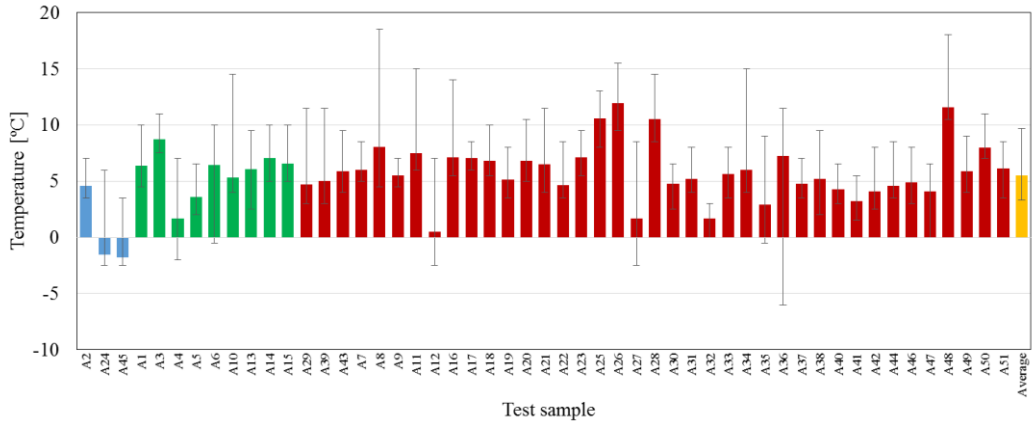

Figure 3. Average, minimum and maximum values of storage temperature of the test sample.

In the majority of the case studies, there was a time where the maximum value of the storage temperature was higher than the limit for the cold storage temperature. Only two case studies (A3 and A32) reach a maximum value of cold storage temperature within the temperature range in which the refrigerator should operate. Figure 4 shows the variation of the cold storage temperature measured in the case study A35. The storage temperature was within the temperature range that ensures food safety and quality during the test period of about 211 hours.

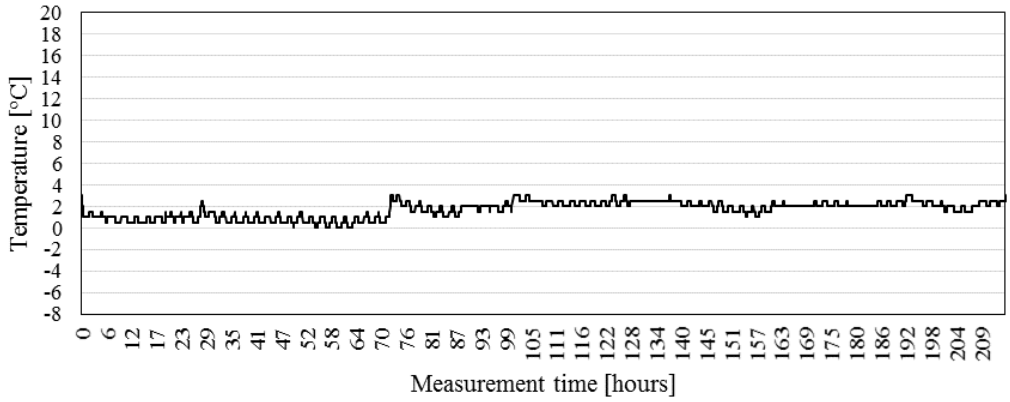

Figure 4. Variation of the cold storage temperature measured in the case study A35.

There is a large range of maximum values of storage temperature within the 51 test cases studied. The test sample reached an average maximum temperature of 9.7 ºC. However, one of the samples (case study A8) reached a maximum value of cold storage temperature of 18.5 ºC. The variation of the storage temperature of test case A8 is shown in Figure 5. A maximum cold storage temperature value that exceeds the limit value of food safety was overcome during 36 hours of the test period.

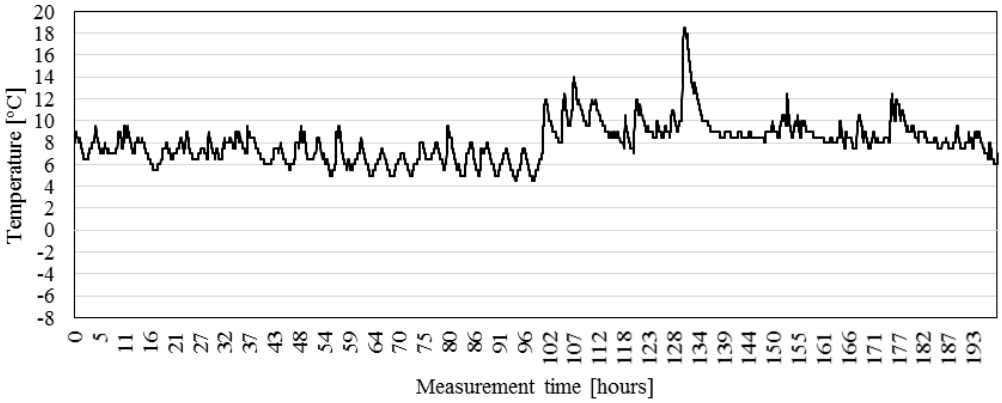

Figure 5. Variation of the cold storage temperature measured in the case study A8.

Conversely, a 3 °C maximum value of cold storage temperature was reached in another case study (A32). This is an operating condition that meets all the safety requirements of the food products stored in the refrigerator. The maximum temperature reached in the majority of the case studies is far above the ideal temperature range for the operation of the appliance. The maximum value of the cold storage temperature is above 10 °C in 37% of the test sample. From the analysis of the temperature variation along the test period for each of the case study, it can be stated that the situation occurs during a short time. Additionally, the increase of the cold storage temperature occurs gradually over time, i.e., the temperature steadily increases over the measurement period. This condition results in the inability of the appliances' refrigeration system withstand the thermal loads arising from: (1) Storing hot food products inside the appliance. The heat transfer by convection and conduction from the food products to the surrounding environment results in a temperature increase; (2) Letting the appliance's door open over a long period of time. This condition determines a thermal load by ambient air infiltration at a much higher temperature.

The minimum value of cold storage temperatures reached during the test period is mainly due to the appliance temperature setpoint and its cooling power. There are quite distinct minimum values of cold storage temperature among the case studies. There are some cases (A4, A6, A12, A24, A27, A35, A36 and A45) where the minimum temperature is lower than the minimum recommended temperature. Thus, food products may freeze inside these appliances. By other hand, there are case studies (A11, A16, A17, A18, A23, A25, A26, A28, A48 and A50) where the minimum temperature is higher than the maximum recommended temperature. The appliances in those case studies should be replaced to avoid health problems due to the ingestion of spoiled food.

Some conclusions may be drawn by the analysis of the values of the minimum cold storage temperature shown in Figure 3. The average value of the minimum cold storage temperature is 3.3 °C, which is suitable a temperature value for food cooling. The minimum storage temperature of cases studies is -6 °C (A36). In this situation, although food security is guaranteed, the food quality certainly is not, due to

the formation of ice crystals in food that will alter its organoleptic characteristics. In the case study A48, the minimum storage temperature is 10.5 ºC. The appliance of this case study put food security at risk. 33.3% of the cases studied have a minimum storage temperature outside the temperatures range suitable for food cooling.

4. CONCLUSION

The high levels of food waste are a global concern. The largest share of food waste is found in households, and more than 50% of this waste could be avoided. In spite of domestic refrigerators present low-risk to the public health, it is in these that occurs most of the food waste at household level. The factors leading to this waste can result from the thermal performance of the appliance, the mismanagement of food stored in to the misuse of the appliance.

This study describes the evaluation of the operative conditions of refrigerators used by the student community at the University of Beira Interior (Covilhã). The experimental study monitored the cold storage temperature on a sample of 51 appliances. The sample devices have an average electric power of 126 W. Their average inner volume is 205 liters (0.205 m^3).

The overall average value of the cold storage temperature is 5.5 ºC. The average values of the minimum and maximum temperatures were 3.3 °C and 9.3 ºC, respectively. Of these values, only the overall minimum value of the cold storage temperature is within the proper storage temperature range. From the data obtained, it can be concluded that the overall operative thermal conditions surpass the upper limit temperature by a small margin (0.5 °C). It was concluded that this value is mostly due to a defective use of the appliances. This temperature value higher than the reference level for ensuring adequate food safety may incur risks to the public health. This figure is largely related with improper behaviour of students, in particular, by the large number of times that the refrigerator is opened unnecessarily, thereby causing an increase in the thermal load by ambient air infiltration.

The practice to reduce this condition consists in information and awareness of users about the negative usage procedures of the appliance and describing how these procedures can be corrected, and consequently improving the thermal performance, ensuring temperature values within a range for a proper food quality and safety.

This study, in addition of providing experimental results on the thermal performance of refrigerators in a community not studied so far, intends to contribute as a reminder of the good practices for reducing food waste, while ensuring food safety of perishables food products cold stored in household refrigerators.

REFERENCES

[1] James SJ, Evans J, James C. A review of the performance of domestic refrigerators. J. Food Eng., 2008, 87:2-10.

[2] Laguerre O, Derens E, Palagos B. Study of domestic refrigerator temperature and analysis of factors affecting temperature: a French survey. Int. J. Refrig., 2002, 25:653-659.

[3] Evans JA, Foster AM, Brown T. Temperature control in domestic refrigerators and freezers. Proc. IIR ICCC 2014, London, UK, June 23-25, 2014.

[4] Peck MW, Goodburn KE, Betts RP, Stringer SC. Clostridium botulinum in vacuum packed (VP) and modified atmosphere packed (MAP) chilled foods. Final Project Report, FSA Project B13006, Institute of Food Research, Norwich, UK, July, 2006.

[5] Mathews P. Sample Size Calculations: Practical Methods for Engineers and Scientists. Mathews Malnar and Bailey, Inc., 2010.

[6] Kresyszig E. Advanced Engineering Mathematics, 9ª Edition, John Willey & Sons, Inc, 2006.