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Development of a Methodology to Measure the Rates of Air Infiltration into Refrigerated Compartments

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ABSTRACT

The infiltration of hot and humid air through the magnetic seals – also called gaskets – of household refrigerators increases the system thermal load and accelerates the frost accumulation on the evaporator coil. The air infiltration is even more pronounced when a manufacturing deviation takes place and prevents the proper closure of the refrigerator doors. An increase in the amount of frost accumulated on the evaporator increases the power consumption and may even jeopardize the refrigerator functioning with considerable impact on the technical assistance costs. The aim of this study was to develop a methodology to measure the rates of air infiltration into refrigerated compartments based on the tracer gas dilution technique. An experimental apparatus was designed and constructed especially for this purpose. The apparatus includes a means of distributing the tracer gas uniformly into the zone, a means of ensuring a uniform concentration both in the vertical and horizontal directions, a means for obtaining the air samples and a gas analyzer to measure the gas concentration at known times. Concentration measurements were taken using the infrared photoacoustic spectroscopy technique. Tests were carried out on three distinct refrigerators, with the compressor on and off and with the concentration decay and constant concentration measurement techniques. It was observed that the tests have a high level of repeatability, with deviations of less than 5% in the air infiltration rate measurements. It was also noted that the two measurement techniques provide practically the same results. Furthermore, it was found that the air infiltration rate is approximately five times higher when the compressor is turned on due to the higher pressure difference at the gasket created by the higher temperature difference. The influence of the rate of the change in the refrigerator temperature over time on the behavior of the air infiltration was also investigated. In addition, adsorption tests were carried out and the results indicated that the adsorption of the tracer gas by the refrigerator materials and gasket is insignificant when compared to the concentration variations caused by air infiltration. Manufacturing deviations were also simulated and it was found that they greatly increase the air infiltration rate through the gasket. To verify that the technique developed is reliable and practical and that it represents a useful tool for the design and analysis of household refrigerators, two new refrigerators were tested. The tests were performed with different gaskets and extra seals in key regions. The results for the variation in the air infiltration were found to be reliable and the technique is practical to apply.

1. INTRODUCTION

Efficient refrigerators may be the key to decreasing energy consumption in a world where household appliances form a significant part of the domestic electricity expenditure. In Brazil around 29TWh/year are used to refrigerate food (Eletrobras, 2011). One cause of refrigerator efficiency loss is the formation of frost on the surface of the evaporator, which decreases the airflow rate through the heat exchanger and increases the thermal resistance between the air and the evaporator. Both of these factors reduce the refrigeration capability of the system. When the refrigerator doors are closed, the main humidity inlet is infiltration through the magnetic seals – also called gaskets. The infiltration of outside air raises the inside temperature and humidity levels, increasing the frost formation and, in no-frost appliances, increasing the defrost cycle frequency.

The air infiltration rate increases substantially when there is a production deviation in the refrigerator flanges, doors or gaskets. The consequences are an increase in frost formation, energy consumption and expenses associated with technical assistance on the part of the manufacturer, since clients will complain about the abnormal quantity of frost.

The warming up of the inside air is not a critical issue in the air infiltration analysis. Boughton et al (1996) considered the contribution of each structural part of the refrigerator to the total thermal load. The gasket represents only 2.7% of the total heat inlet. The thermal loads taken into account were the unidirectional heat transfer through the doors and walls, the bidirectional heat transfer at the door flanges, the unidirectional heat transfer through the gaskets, the heat conduction through the mullion and the heat added by the frame heater. This article also shows that the thermal load brought by the defrost heater is above 5% of the total thermal load. When this is added to the increase in energy consumption due to the longer compressor cycle after the defrosting, it can be easily noted that the major disadvantage of air infiltration in refrigerated compartments is, indeed, the humidity inlet.

Afonso and Castro (2010) compared the air infiltration rates of new and used gaskets by applying the tracer gas technique. They employed sulfur hexafluoride (SF_6) and followed the method of concentration decay. The authors concluded that the heat transfer due to air infiltration with the new gasket is 500% lower than that with the used gasket. However, the authors may have misunderstood the measured values for the infiltration rates – an issue which was probably related to the unit of time used in the calculations. The infiltration rate stated by the authors – 2.1 air changes per hour in a cabinet with new gaskets – implies approximately 190g of frost formation per day, considering an ambient temperature of 24°C and humidity of 54%. To reach this amount of frost, Melo et al. (2012) had to place a bowl of water in the refrigerator and heat it up continuously for 9 hours. Therefore, the main contribution of the article of Afonso and Castro is the use of the tracer gas technique inside a refrigerated compartment.

A workbench was designed and constructed to evaluate the air infiltration rate in refrigerated compartments. The approach used was the tracer gas technique applied to two methods: concentration decay and constant concentration. Tests were performed with the refrigerator turned on and off, with and without communication between the compartments and with and without fans for better air circulation.

2. AIR INFILTRATION

Air infiltration is the nonintentional exchange between inside and outside air. The refrigerator envelope permeability is mainly dependent on three factors: type of flow, difference between inside and outside pressure and size and distribution of the gaps. Assuming the flow is always laminar and equally distributed along the whole gasket perimeter, for similar gap sizes the pressure difference will be the dominant parameter in terms of the air infiltration rate. The pressure difference is directly dependent on the temperature of inside and outside air. According to Liddament (1986), there is a region known as the neutral plane, where inside and outside pressures are equivalent and there is no infiltration. Assuming the gaps are symmetrically distributed and the temperatures are uniform and constant, the neutral plane is in the middle of the height of the refrigerator. This means that the inside pressure will be lower or higher than the outside pressure depending on whether it is above or below the neutral plane. Thus, warm and humid air will infiltrate through the upper part of the gasket, while cold and dry air will flow out through the lower part of the gasket. Figure 1 illustrates the pressure gradient on the refrigerator gasket for this ideal case.

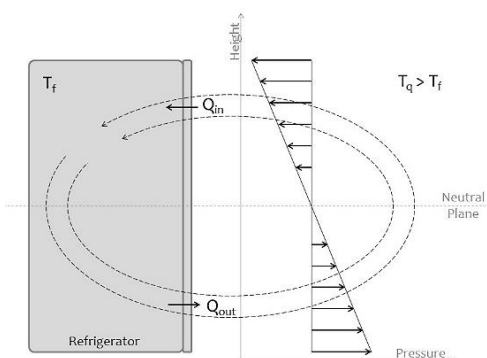


Figure 1 - Pressure differences responsible for air flux

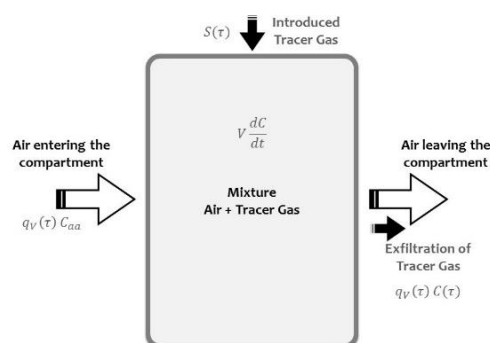


Figure 2 - Mass balance from which the infiltration equations are developed

The unit used for measuring air infiltration is the “air infiltration rate” (I), a ratio between the volumetric flow of infiltrated air (Q) and the internal volume of the considered compartment (V). In other words, this unit indicates how many times in a specified period a volume of air equivalent to the volume of the compartment is exchanged with the surroundings. Equation 1 shows this ratio.

$$I = Q/V \quad (1)$$

The volumetric flow of infiltrated air can be calculated using Equation 2, which is valid for flows through gaps under laminar and turbulent regimes. The flow exponent (n) is dependent on the flow regime: 0.5 for completely turbulent, 1.0 for laminar and intermediate values for mixed flows. The flow coefficient (k) is dependent on the gap geometry and assumes a specific value for each opening form.

$$Q = k (\Delta p)^n \quad (2)$$

2.1. Tracer Gas

A tracer substance is a material which follows the desired flow and is easy to identify. The tracer gas technique was used in this work to quantify the air infiltration rates through the gaskets. Unfortunately, there is no gas that is at the same time easy to identify, unflammable, poses no health risk, does not react with other air components and has a similar density to air. Therefore, the gas chosen was sulfur hexafluoride (SF_6), which has a density of 6.07kg/m^3 at 25° – approximately five times denser than air. The greatest advantage of SF_6 is the low measuring limit: 0.1ppm, which enhances the quality of the measurements (INNOVA, 2013).

The tracer gas technique can be used employing three different methods: concentration decay, constant emission and constant concentration. The equations for all of the methods are based on a mass balance, as shown in Figure 2 and Equation 3.

$$\frac{d(V C(t))}{dt} = Q(t) C_a - Q(t) C(t) + S(t) \quad (3)$$

where V is the volume of the compartment, C is the tracer gas concentration inside the compartment, Q is the infiltrated air flow rate, C_a is the tracer gas concentration in the outside air and S is the injected tracer gas flow rate. Sulfur hexafluoride is artificial and rare, thus its concentration in the outside air can be considered zero. Replacing Equation 1 in Equation 3 and integrating the results over time results on Equation 4, where C_0 is the initial tracer gas concentration inside the compartment.

$$e^{-It} = \left[\frac{S/V - I C}{S/V - I C_0} \right] \quad (4)$$

Dividing Equation 4 by I , the ratio S/Q is obtained, which is the tracer gas concentration approached by the system under steady-state conditions. On reorganizing the terms, the General Equation of Dilution (Equation 5) is found. This is the base equation for the three existing methods.

$$C(t) = S/Q [1 - e^{-It}] + C_0 e^{-It} \quad (5)$$

Two of the three methods were employed in this study: concentration decay and constant concentration. The former method is the simplest: tracer gas is injected in the compartment and, after its concentration is uniformly dispersed, the exponential concentration decay is measured. On a logarithmic plot the concentration decay over time is a straight line, as mathematically proved when replacing $S = 0$ in Equation 5 and isolating I :

$$I = \frac{1}{t} \ln \left(\frac{C_0}{C} \right) \quad (6)$$

Etheridge and Sandberg (1996) endorse the use of the constant concentration method to measure the infiltration rate in compartments with more than one interconnected zone. This is particularly interesting for household refrigerators with dampers. In this method, there are two different tracer gas injections: the first to raise the inside concentration to the desired level, and a periodical one to maintain the concentration at a constant level. The periodical injection makes a data acquisition system and peripheral actuators, like valves and controllers, necessary. This method is thus more complex and expensive. The constancy of concentration allows the unique characterization of a compartment with zones of different infiltration rates, since the total infiltration is proportional to the added tracer gas. The fact that the concentration is the same in all zones, cancels the diffusion and air exchange between them. If distinct characterization of the different zones is desired, more tests must be conducted or more injection controls and measuring systems need to be used. For the unique characterization, Equation 7 summarizes the calculation of air infiltration rate:

$$I = \frac{1}{V} \frac{\sum_0^t Q(t)}{\sum_0^t C(t)} \quad (7)$$

The standard ASTM E741 (2012) provides details of the tracer gas technique applied to buildings. Some recommendations were applied in this study as a guideline for testing refrigerated compartments:

- Uniformity of concentration: two concentrations at different heights cannot differ by more than 10% from the compartment average. This characteristic was verified in the beginning and at the end of every test;
- Representative sampling: the sampling must be carried out at a minimum of three equally spaced horizontal points, at more than one height level and at pre-determined times;
- Minimal test duration: calculated according to each test concentration and the variation levels.

2.2. Adsorption onto Polymers

Every solid material has pores on its surfaces and the material structure dictates the size and amount of pores. Suspension molecules in contact with these surfaces may be repelled, adsorbed, solubilized or permeated according to the polarity of the molecules and the ratio between the sizes of the pores and molecules. At temperatures lower than typical ambient temperature, it is unlikely that chemical reactions between these elements occur due to the lack of free energy. On the other hand, physical reactions can take place. Due to their nonpolar and amorphous structure, polymeric surfaces tend to adsorb and solubilize to some extent all nonpolar gases (Norton, 1957). Therefore, as the tracer gas used in this work (SF_6) is amorphous, it will be adsorbed to some degree. The adsorption level will be proportional to the partial pressure of the gas, that is, to its concentration in air. The refrigerated compartment is mainly composed of polymeric materials and if the amount of gas adsorbed is significant the infiltration results will be affected.

The commonly used methods for measuring adsorption, like infrared spectroscopy or gas chromatography, are not sensitive enough (3% and 3ppm, respectively) for the expected levels of adsorption (Salmoria, 2013). In this case, the measuring equipment of the workbench (which has a detection limit of 0.01ppm) was used along with a borosilicate glass recipient designed exclusively for this purpose. Borosilicate glass does not adsorb considerable amounts of molecules larger than helium at temperatures under 700°C . Samples of the refrigerator polymers and SF_6 were placed inside the recipient and the concentration decay was measured. Further details will be given in the following sections.

2.3. Materials and Methods

Five refrigerators were tested: “refrigerator A” has 439 liters and is comprised of two completely distinct compartments. The four other refrigerators have communicating compartments and are named: B (586 l), C (352 l), D (429 l) and E (422 l). An easily interchangeable measuring device was designed and installed inside the refrigerators. The device is composed by four main sequential parts: sampling end, passage joint, valve tree and analyzer. The first part through which the air passes is the sampling end, composed of three acrylic tubes with holes in their walls, a mixing chamber and an outlet tube, as shown in Figure 3-a. Four sampling ends were employed at different heights to ensure uniformity of concentration. Sequentially, the air is sucked through the passage joint, which is responsible for connecting the inside and the outside compartments without leakages, as can be seen in Figure 3-b. The fifth hole, shown in Figure 3-c, is used for adding or returning gas to the compartment after the measurements have been taken. Inside the compartment, a stainless steel tube injects the gas at the center of the horizontal plane 16cm from the compartment ceiling. The four tubes are connected to the valve tree, where one or more sampling ends can be selected for analysis. The next step is the gas analyzer, which measures the gas concentration and sends the sample back to the

compartment. The tubes are made of polytetrafluoroethylene (PTFE) to avoid the adsorption of large amounts of SF₆ onto the tube walls. Specific connections were developed to ensure self-sealing, as shown in Figure 3-d.

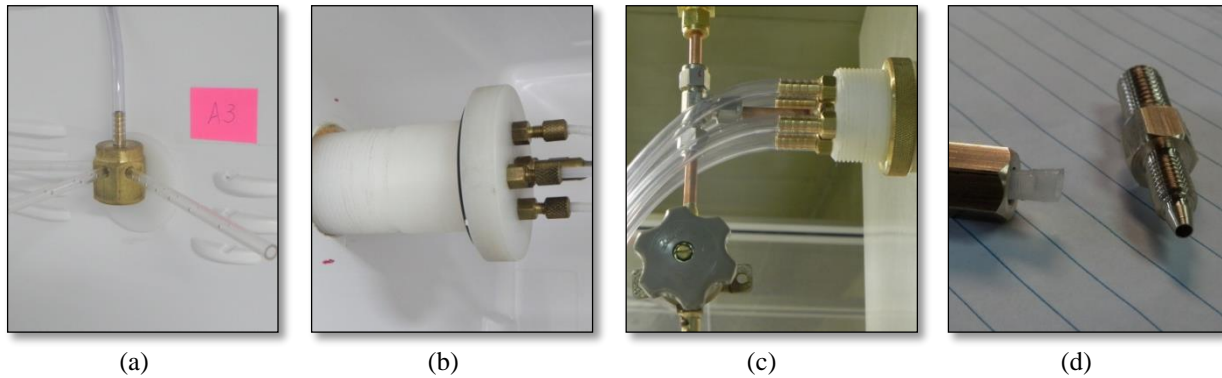


Figure 3 - Workbench. (a) Sampling end; (b) Passage joint; (c) Return duct; (d) Self-sealing joint.

Six type-T thermocouples with welded standard copper masses were used to measure the temperature in the tests with the refrigerator turned on. A data acquisition system was used to send the information to the computer for data analysis. For the constant concentration method, a controlling system for the injection of SF₆ was assembled using a stainless steel cylinder of 75ml, a pressure-controlling valve, a needle valve with 0.004 maximum C_v and a solenoid valve. The solenoid valve is controlled by a PWM (Pulse Width Modulation) logic, which opens and closes completely under the predefined frequency sent by the controller. Figure 4 illustrates the above-explained SF₆ circuits.

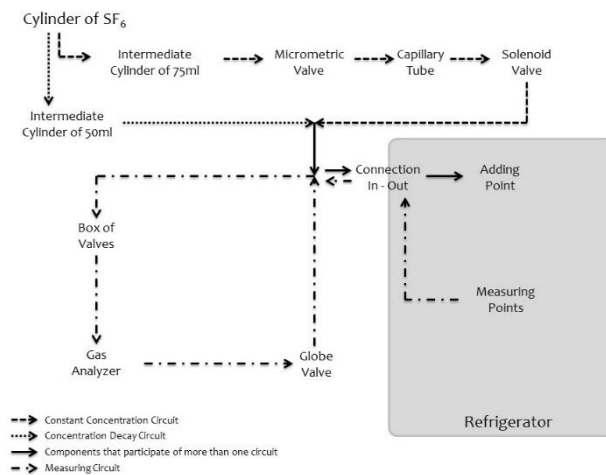


Figure 4 - SF₆ Circuits

The exact volumetric flow of air that passes through the assembled circuit needs to be known to determine the air infiltration by the constant concentration method. Therefore, the flow through the needle valve – capillary tube – solenoid valve was measured on a specific workbench, resulting in $(1.41 \pm 0.01) \cdot 10^{-5}$ m³/s.

The gas analyzer is based on the PAS (Photoacoustic Spectroscopy) principle: each existing molecule vibrates naturally at a specific infrared frequency and thus it can be excited at that frequency (LumaSense, 2011). During a measurement, the air – SF₆ mixture is inserted into the purged measuring chamber, the infrared light source is turned on, the desired frequency filter is selected and a chopper wheel rotates, making the energy intake pulsate. When the air sample receives this energy, it heats up and cools down repeatedly, generating pressure waves that are captured by two microphones installed inside the measuring chamber. It is important to verify that there is no other gas with a similar characteristic frequency, which could interfere with the measurement. The applied filter has a measuring limit of 0.1ppm (10 times greater than the detection limit).

The test procedure is as follows: the gas analyzer is turned on and the steady state is established; the initial SF₆ concentration is verified (must be lower than the measuring limit of the filter); the initial SF₆ load is added to the compartment; some time is given for the gas to dilute through the compartment; the vertical homogenization is tested. If the compressor is on, the temperatures are recorded and time is given for the refrigerator to reach the steady state. When the constant concentration method is used, the periodic injection of tracer gas is started. Finally, the test is monitored for the predetermined period, the vertical homogenization is again verified and the test is completed.

3. EXPERIMENTAL ANALYSIS AND RESULTS

The main goal of the experimental analysis is to verify that the proposed methodology is appropriate for measuring the air infiltration rate through gaskets of refrigerated compartments. To achieve this aim, the following topics were addressed: adequacy to the ASTM E741 standard, concentration decay methodology, constant concentration methodology, tracer gas adsorption, considerations regarding driving forces, practical applicability.

3.1. Adequacy to ASTM E741 Standard

The compartment temperature for the tests with the refrigerator turned off was the same as the outside temperature (around 21°C). For the tests with the compressor turned on, the fresh food compartment was maintained at around 4°C and the freezer compartment at around -18°C. Special tests were conducted with the compressor constantly turned on (sometimes called true steady state tests) when the temperatures reached around -30°C in the freezer and 0°C in the fresh food compartment. A fan was installed on the compartment floor to help homogenize the SF₆ concentration and was kept at 6V during the tests. Undesired inlets were sealed with industrial silicone. The initial mass of injected gas was around 0.02g, a value calculated for a starting concentration of around 10ppm.

For the concentration decay method, the minimum test duration must be one complete air change. This was defined based on the first test: it took 29 h for a complete air change to be performed, thus the minimum duration was defined as 30 h. For the constant concentration method, Equation 8 defines the minimum test duration based on the concentration and variation levels (ASTM E741, 2012). The variation is calculated from the average and standard deviation of ten sample collections. On estimating 0.2 air changes per day for the refrigerator turned off, $I|_{estimated}$, the minimum duration is of 18 h. For the refrigerator turned on, the estimate for $I|_{estimated}$ rises to 0.8, resulting in a minimum duration of 5 h. Note that $c_{initial}$ is the initial tracer gas concentration, c_{final} is the final tracer gas concentration and c_{target} is the target concentration level.

$$duration_{min} = \max \left(\frac{100}{I|_{estimated}} \vartheta_{GA} ; \left| \frac{c_{final} - c_{initial}}{0.02 I|_{estimated} c_{target}} \right| \right) \quad (8)$$

The uniformity of the concentration was verified using five measurements from each of the four sampling ends at the beginning and at the end of each test. In all tests, the difference between each measurement and the average was below 5%, which is better than the 10% stated as the maximum limit in the ASTM standard.

3.2. Concentration Decay Methodology

As stated in Equation 6, the absolute value for the inclination of the concentration curve plotted on a log graph is numerically equal to the air change rate. The first tests were performed on the fresh food compartment of refrigerator A, which has completely separate compartments. Figure 5-a shows the results for a test with the compressor turned off, while Figure 5-b shows the results for a test with the compressor turned on. Figure 5-a results in 0.15ACD (Air Changes per Day) and Figure 5-b results in 0.79ACD. In Figure 5-b the value is 5.3 times greater due to the driving force for the air circulation that is generated when the inside temperature decreases. Note that the air change rate oscillates over time due to the on-off cycles of the compressor, which produce a certain temperature oscillation in the compartment. All of the tests were performed more than once. For the compressor turned off, the results varied by only 3.3% while for the compressor turned on the results varied by less than 5%.

The second refrigerator tested, refrigerator B, has two communicating compartments separated by a damper. The air way was sealed and some tests were performed in the fresh food compartment. As the single evaporator is placed in

the freezer, these tests were performed with the compressor turned off. Figure 6-a shows the results for this compartment. Figure 6-b shows the results of a test simulating a product deviation: a piece of metal was placed on the door flange, leaving a section of the gasket unsealed. The air infiltration rate is 64 times higher, reaching 3.33ACD. The infiltration rate for the original sealing is 0.05ACD, which is three times lower than the result for refrigerator A. This difference is due to the inappropriate storage of refrigerator A, which was left for five years in a warm warehouse and thus the gasket polymer may have degraded. Some tests were performed with refrigerator B turned on and without any seal between the compartments. The air infiltration rate measured for the refrigerator turned on was 0.91ACD.

The third refrigerator tested, C, also has two communicating compartments separated by a damper. The concentration decay test for the whole refrigerator turned on resulted in 1.00ACD. Oscillations in the concentration values can be noted in Figure 7. This was the reason for carrying out the true steady state tests, which resulted on 0.86ACD.

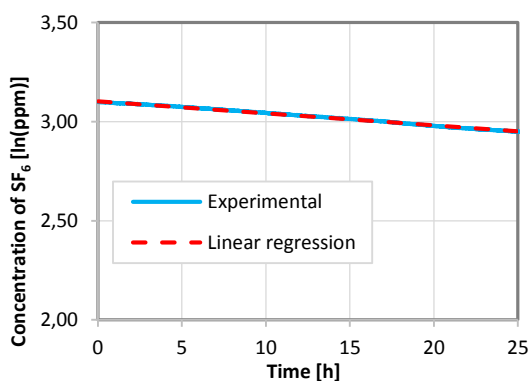


Figure 5a - Decay test –refrigerator A off

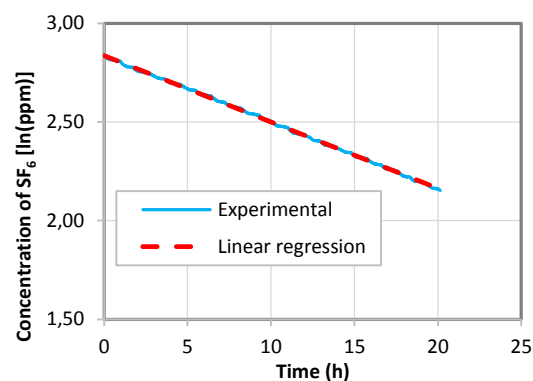


Figure 5b - Decay test – refrigerator A on

3.3. Constant Concentration Methodology

For refrigerator A, the results for the fresh food compartment obtained with the constant concentration method were very similar to the concentration decay method: 0.71ACD for the compressor turned on and 0.22ACD for the compressor turned off. For refrigerator B, the global air infiltration rate was 0.97ACD for the compressor turned on and 0.07ACD for the compressor turned off. This low air change rate increases the duration of the test and makes it difficult to control the gas injection. Therefore, the repeatability was low. Another advantage of the turned on test is that the homogenization of the SF₆ concentration occurs around 12 times faster. For refrigerator C turned on, the global infiltration rate found was 0.98ACD and for the true steady state it was 0.86ACD. Table 1 shows the results. Figure 8 shows the results for a constant concentration test carried out with refrigerator B turned on.

3.4. Tracer Gas Adsorption

To verify whether the adsorption of SF₆ on the inside of the refrigerator is significant, firstly it is necessary to identify the polymers, since their composition may indicate chemical affinity. According to the book *Plastics Design Library*, the inner wall of refrigerators is typically made of HIPS (High Impact Polystyrene). The material of the gasket, however, is not generally defined. To determine this material two tests were performed: flame characterization and infrared photospectroscopy (or FTIR). The flame test determines the global characteristics of the polymers (Piva and Wiebeck, 2004) and FTIR determines interatomic bonds present in the material (Nicolet, 2001). The results indicate the gaskets analyzed are made of PVC (polyvinyl chloride), which has halogen elements that tend to react with sulfur.

The second step was the design and construction of a well-sealed borosilicate glass recipient, for which conical joints, PTFE tapes, keck joints and industrial silicone were used, as shown in Figure 9. Firstly, the infiltration rate of the empty compartment was measured by the concentration decay method. Parts of gaskets and HIPS were then placed in the recipient and the infiltration was again measured. The results indicate the air infiltration and the adsorption of gas. Based on a comparison with the baseline, the amount of gas adsorbed can be determined. Figure 10 shows the results: 10-a, empty recipient; 10-b, recipient with gasket inside; and 10-c, recipient with HIPS inside. The average results are 0.30ACD for the empty recipient, 0.31ACD for the recipient with the gasket and 0.29ACD for the recipient with HIPS. These results show that adsorption onto the gaskets and HIPS is low and can be neglected in the current analysis.

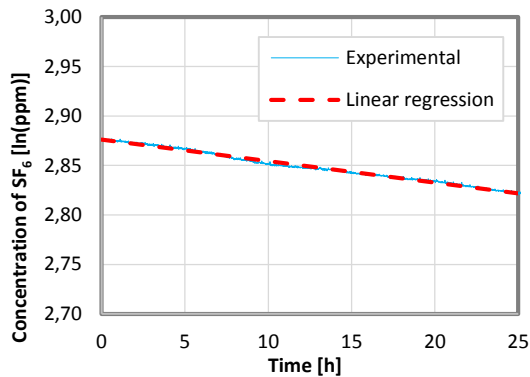


Figure 6a - Normal decay test – refrigerator B fresh food

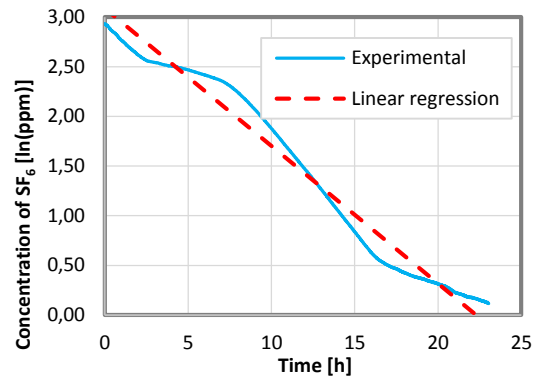


Figure 6b - Decay test with intentional aperture – refrigerator B fresh food

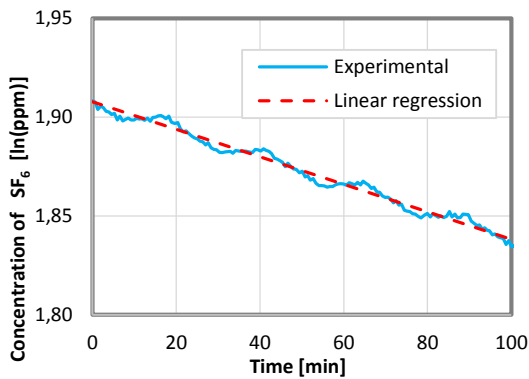


Figure 7 - Decay test – refrigerator C on

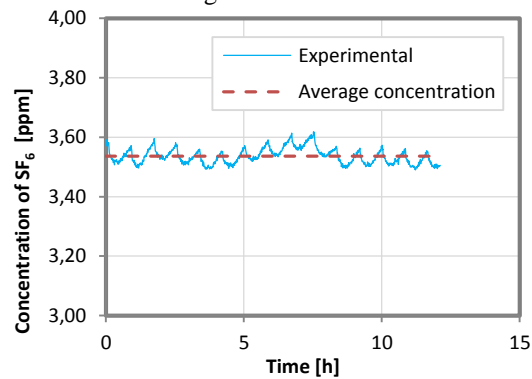


Figure 8 - Constant concentration test – refr. B on

Table 1 - Summary of the test results

	Refr. A On	Refr. A Off	Refr. B On	Refr. B Off	Refr. C On	Refr. C - True Steady state
Decay	0.79	0.15	0.91	0.05*	1.00	0.85
Constant	0.71	0.22	0.97	0.07	0.98	0.86

*fresh food only

3.5. Considerations on Driving Forces

According to the tests performed in steady state and in true steady state, the air infiltration rate is a function not only of the temperature difference but also of the thermal regime imposed on the refrigerator. During the on cycle of the refrigerator the infiltration rate is greater than during the off cycle: for the concentration decay method, the decrease during the off cycle is much smaller than during the on cycle; and for the constant concentration method, the average is constant, but the concentration increases during the off time and decreases during the on time. These variations result in the saw teeth seen in figures 7 and 8. They also indicate that the variation in temperature over time is a key factor in the analysis: it generates a pressure variation inside the compartment, which sometimes favors the infiltration and sometimes hinders it. It is important to point out that this behavior is independent of the evaporator fan, since some tests were performed with the fan turned on 100% of the time and the saw teeth behavior was also observed.

3.6. Practical Applicability

Two other refrigerators were tested to verify the practical applicability of the method developed: refrigerator D (top mounted) and refrigerator E (bottom mounted). Besides comparing the refrigerators, the influence of different gasket types, extra sealing options and different ambient temperatures were also evaluated.



Figure 9 - Glass recipient developed for the adsorption tests

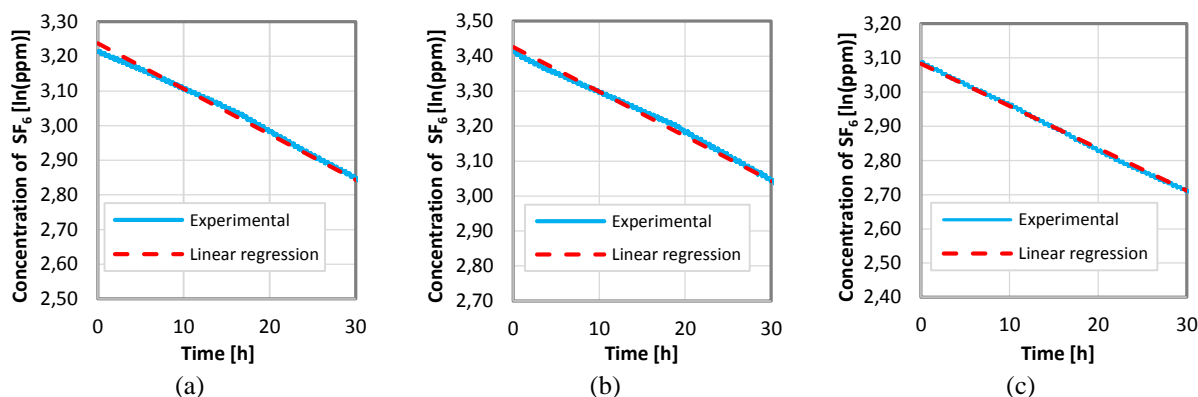


Figure 10 – Infiltration in glass recipient. (a) Empty. (b) With gaskets placed inside. (c) With HIPS placed inside.

Good results were obtained on comparing the two refrigerators. Using the same gasket type and the same fans (one in each compartment, both at 6V), refrigerator D resulted in a value of 1.74ACD while the value for refrigerator E was 1.37ACD. The difference in terms of sealing is clearly shown and is due to the inequality of the compartment sizes: the freezer gasket perimeter is greater on the bottom mounted appliance, meaning that the influence of the freezer compartment is more pronounced in refrigerator E than in refrigerator D. The colder the compartment, the lower the internal pressure and hence the more suctioned the door will be (Afonso and Castro, 2010). This shows that the results are in accordance with the physical analysis presented in the literature.

The technique was also interesting for comparing different types of gaskets. The air infiltration rate of refrigerator E increased by around 9%, from 1.37ACD to 1.49ACD, when the original gasket was replaced by a similar model. The air infiltration rate of refrigerator D increased by around 7%, indicating the method is applicable for different products.

Cases with a worsening of the state of the sealing were tested, as shown in Figure 6-b. For refrigerators D and E, a better sealing option was also tested. Industrial silicone was placed on the door flange and inside the gasket channel, minimizing the infiltration through the edges of the polymeric seal. Once more the technique was shown to be applicable: the infiltration rate in refrigerator E decreased by 36.5% and that in refrigerator D decreased by 34.9%.

The last comparison investigated was between different ambient temperatures: 32°C and 21°C. The air change rate was 25% lower at the higher temperature. Once again this can be attributed to the pressure difference: the refrigerators were off with doors open until the climate chamber reached 32°C. When the refrigerator doors were closed and the system was turned on the pressure variation was greater than in the other tests, since the air temperature decreased from 32°C to -18°/5°C. The consequence is a greater sucking force at the doors, which provides better closure, decreasing the air infiltration rate.

4. CONCLUSIONS

The goal of this work was to develop an experimental technique capable of identifying product deviations that affect the infiltration rate in refrigerated compartments. To reach this goal, a methodology and a workbench were developed.

The measurements carried out show a good level of repeatability, with differences lower than 5% between the tests, except for the constant concentration method for refrigerator B turned off. The influence of the temperature difference on the air infiltration rate cannot be neglected: an increase in the temperature difference increases the infiltration driving force and leads to a greater infiltration rate until the point at which the suction of the door is sufficient to overcome the driving force and the infiltration starts to decrease. One example of this is the increase from 0.15ACD to 0.79ACD for refrigerator A when it was on. It is also important to take into account the thermal regime under which the refrigerator is operating: the temperature variation over time plays a significant role in defining the pressure difference between the inside and the outside of the compartment. One example of this is the difference in the results for refrigerator D under different ambient temperatures.

When the refrigerator is turned on, the air infiltration rate is higher than when it is turned off and therefore any experimental errors are mitigated, making the 'turned on' regime preferable. The effect of the SF₆ adsorption onto the refrigerator polymers is small (6% in the worst case), and is even smaller when the refrigerator is turned on: the free energy for chemical reactions is lower and the effects of a fixed error are diminished.

The constant concentration method generates similar results to the concentration decay method, particularly when the refrigerator is turned on. The constant concentration method is more complex and expensive than the concentration decay method, so it can be substituted by the simplest option without leading to significant errors.

Finally, the potential of the study was verified by the tests with intentional openings, different types of gaskets and additional sealing methods. Product deviations can be easily identified through the significant increase in the air infiltration rate: the turned off fresh food compartment of refrigerator B increased from 0.05ACD to 3.33ACD with the intentional opening, corresponding to 64 times more infiltration. In refrigerators D and E, the change in the sealing method resulted in around 36% less air infiltration. This means that not only product deviations, but also product improvements are easily identified and quantified through the developed technique. Thus, it can be concluded that the major goal of this work was fully achieved.

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