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ABSTRACT

This paper outlines an alternative test method to evaluate the energy consumption of frost-free refrigerators and freezers for residential applications. While the standardized methods require the refrigerating appliance to be kept running according to its onboard control system, which usually drives the refrigerator through an on-off cycling pattern, the proposed approach assesses the refrigerator energy performance in the steady-state regime, being therefore much faster and more reliable. In this procedure, the cooling capacity is matched to the cooling loads by PID-controlled electrical heaters installed within the refrigerated compartments, so that the compartment temperatures are kept at the desired standardized levels. Comparisons between the experimental results obtained using the steady-state energy (SSE) test and the standardized procedures showed that the former follows closely the trends observed for the latter.

1. INTRODUCTION

Countries all over the world, particularly the most developed ones, have been adopting policies and regulations to promote the rational usage of energy. Acknowledging that the refrigerating appliances play an important role in residential energy consumption – generally estimated to account for 10% of the total energy produced worldwide (Melo and Silva, 2010) – energy labeling programs and product approval standards have played a fundamental role in government strategies to enforce the production of highly efficient appliances (Coulomb, 2006).

Different test procedures have been used to assess the energy consumption of household refrigerators (Bansal, 2003, Yashar, 2003, Hermes *et al*., 2004), the most notable being the international energy test standards (ISO 8561, 1995, ISO 15502, 2005, IEC 62552, 2007), mainly adopted by refrigerator manufacturers in Europe and Latin America. In general, the standardized energy tests require the refrigerator to be tested using its onboard control system, which is usually comprised of a thermostat that turns the compressor on and off according to a cycling pattern in order to match the cooling capacity to the cabinet thermal loads. One should note that the former is usually twice the latter and thus that the refrigerator runtime is around 50% of the whole cycle.

As a consequence of the cycling operation, the standardized tests are not only time consuming – a single test generally takes a whole week to conduct if both product instrumentation (~1 day) and experimental runs (~4 days) are taken into account – but also considers a limited set of averaged performance indicators (e.g. power consumption, compartment temperatures) while other important design parameters are neglected, such as thermal load, cooling capacity and coefficient of performance (*COP*). In order to overcome these drawbacks, the present study is aimed at devising an alternative test method to assess the energy consumption of frost-free refrigerators that (i) provides reliable results, (ii) can be easily carried out, and (iii) requires a considerably shorter testing time. The proposed procedure is clearly not intended as a basis for the final product approval, since this is dependent on government regulations and, therefore, must adhere to standardized policies before the product can be placed on the market. Instead, the test method proposed herein is aimed at replacing the costly and time consuming standardized tests adopted during the product ideation and development processes for the sake of component matching, refrigerant charge and capillary tube adjustments, and so forth, which can make the development of new refrigeration systems an expensive endeavor.

2. TEST STANDARDS

The most relevant and influential test methods devised to standardize the operating conditions and procedures to assess the energy consumption of household refrigerators and freezers are the North American AHAM HRF-1 (2004), the Australasian AS/NZS 4474.1 (1997), the Japanese JIS C 9607 (1996), and the international standards: ISO 8561 (1995), ISO 15502 (2005) and IEC 62552 (2007). The test conditions for each of these test standards are summarized in Table 1.

According to the AHAM HRF-1 (2004) standard, the refrigerator must be tested with the surrounding environment at 32.2ºC and 75±5% relative humidity. The average fresh-food compartment temperature must be kept at 7.2ºC and the frozen-food (freezer) average temperature at -9.4 ºC or -15 ºC, depending on the product classification. The test must last at least 3 hours and not exceed 24 hours. During the test period, the compressor must complete two or more on-off cycles. Door-openings are not required.

Similarly, the AS/NZS 4474.1 (1997) standard also requires the refrigerator to be tested following a cycling pattern under ambient conditions of 32ºC and 75±5% relative humidity. No door openings are needed. The fresh-food compartment must be kept at 3ºC and the freezer at -9ºC or -15ºC, also depending on the product classification. The energy consumption must be monitored and recorded until it reaches 1 kWh or the test time exceeds 16 hours.

The Japanese standard (1996) requires two test runs to be performed, one at 15ºC and another at 30ºC ambient temperature, both with a relative humidity of 75±5%. This standard adopts three classification grades depending on the freezer compartment temperature (-6ºC, -12ºC or -18ºC), whereas the fresh-food temperature must be kept at 3ºC, independently of the product classification. Differently from the other standards, this one requires door-openings with the door fully opened for at least 5 s. The test must last 24 hours.

ISO 8561 (1995) used to be the international standard for testing frost-free refrigerators until 2005, when it was replaced by ISO 15502, which in turn will be replaced by IEC 62552 (2007). However, the ISO 15502 remains in use in Europe and the ISO 8561 is still adopted in Latin America, particularly in Brazil. In general, all of these standards follow a similar test procedure. Firstly, the refrigerator should be tested according to its climate classification: for subtropical regions (N-class) the test is carried out at an ambient temperature of 25.0±0.5ºC; and for tropical regions (T-class) the ambient temperature is 32.0±0.5ºC. According to these standards, the refrigerator power consumption must be monitored during a period of 24 hours comprised of an integer number of on-off cycles and at least two defrosting cycles. The refrigerator must be instrumented with loading packages made of an artificial substance whose specific heat is equivalent to that of frozen meat. Some of these packages have T-type thermocouples mounted at their centroid and are known as M-packages. Two tests must be carried out, one above and another below the reference temperature, for instance, -18ºC for the freezer compartment and 5ºC for fresh-food compartment. The energy consumption is calculated from a linear interpolation using both test runs.

Table 1: Standardized test conditions for energy consumption evaluation

Test standard	Year	Domain	Ambient (ºC)	Fresh-food (ºC)	Freezer (ºC)
AHAM HRF-1	2004	North America	32.2	7.2	-9.4 or -15.0
AS/NZS 4474.1	1997	Australasia	32.0	3.0	-9.0 or -15.0
JIS C 9607	1996	Japan	15.0 or 30.0	3.0	-6.0, -12.0 or -18.0
ISO 8561	1995	International	25.0 or 32.0	5.0	-6.0, -12.0 or -18.0
ISO 15502	2005				
IEC 62552	2007				

3. PROPOSED APPROACH

The difference between the proposed approach and the standardized tests mentioned above lies fundamentally in the strategy adopted for controlling the freezer and fresh-food compartment air temperatures. During the standardized tests the temperatures are set by the refrigerator onboard control system – for instance, a thermostat (a device that turns the compressor on and off, according to the temperature of one compartment, usually the freezer) and a damper (a thermo-mechanic device that regulates the airflow according to the desired temperature of one compartment, usually the fresh-food) – thus imposing a transient cycling pattern on the refrigeration system.

The cycling behavior not only increases the time required to complete the test, but also leads to several difficulties associated with analyzing and reducing the experimental data. In order to overcome these drawbacks, the proposed approach consists of testing the refrigerator under the steady-state condition, where all the response variables (pressures, temperatures, power consumption, and so forth) are held constant over time.

In this study, the steady-state condition was achieved by setting the compartment air temperatures to fulfill the requirements of the test standard (see Table 1) through PID-driven electrical heaters strategically placed within the fresh- and frozen-food compartments, as depicted in Fig. 1. The exceeded cooling capacity is, therefore, overridden by heat generation inside the refrigerator in such a way that the test is carried out in the steady-state regime. In this study, an analogical control strategy has been adopted, where two phase-angle solid-state relays drive the electrical heaters independently according to the temperature of each compartment. During the tests, the thermostat must be deactivated while the damper is fixed at a predefined position.

The proposed methodology was firstly evaluated using a 400-liter top-mount frost-free refrigerator running with 47 g of the refrigerant HC-600a. The compartment air is propelled by a radial fan installed in the upper part of a tube-fin no-frost evaporator, whereas the condenser air is buoyantly driven across a wire-and-tube array. The refrigeration system is comprised of a thermostatic damper that regulates the air distribution among the compartments, thus controlling the fresh-food temperature, whereas the freezer temperature is controlled by a thermostat which switches the compressor on and off.

In order to assess the system overall energy consumption using steady-state data, the cabinet thermal load should first be calculated using the ambient temperature (T_a), and the temperatures and thermal conductances (*UA*) of each compartment obtained beforehand from the so-called reverse heat leakage (RHL) tests (Vineyard *et al.*, 1998, Gonçalves *et al.*, 2000, Gonçalves *et al.*, 2011, and Sim and Ha, 2011). After the RHL test, the system is switched on with its onboard controls (thermostat and damper) deactivated, thus allowing the internal temperatures to be adjusted by the PID-driven electrical heaters.

The data is reduced as follows. Under the steady-state condition, the cabinet thermal load, Q_t, is calculated from the following energy balance in the refrigerated cabinet:

$$Q_t = UA_{fz}(T_a - T_{fz}) + UA_{ff}(T_a - T_{ff}) + W_{e,f} \tag{1}$$

where $W_{e,f}$ is the evaporator fan power [W], and the subscripts "fz" and "ff" refer to the freezer and fresh-food compartments, respectively. The cooling capacity, Q_e, is then obtained by taking into account the thermal load and also the electrical power dissipated by the heaters:

$$Q_e = Q_t + W_{fz} + W_{ff} \tag{2}$$

In addition, when the refrigerator is operating according to a cycling pattern, all energy transferred into the refrigerated compartments during an on-off cycle must be removed by the cooling system during the compressor runtime, so that the following energy balance over a whole cycle applies (Hermes *et al.*, 2009):

$$Q_e t_{on} \cong \left(UA_{fz}(T_a - T_{fz}) + UA_{ff}(T_a - T_{ff})\right)(t_{on} + t_{off}) + W_{e,f} t_{on} \tag{3}$$

Thus yielding

$$\tau \equiv t_{on}/(t_{on} + t_{off}) \cong (Q_t - W_{e,f})/(Q_e - W_{e,f}) \tag{4}$$

Hence, the monthly energy consumption can be calculated as follows:

$$EC = 0.72\tau(W_c + W_{e,f}) \tag{5}$$

where the 0.72 coefficient is the conversion factor from [W] to [kWh/month]. The system coefficient of performance, COP, is calculated from the ratio between the cooling capacity and the total power consumption:

$$COP = Q_e/(W_c + W_{e,f}) \tag{6}$$

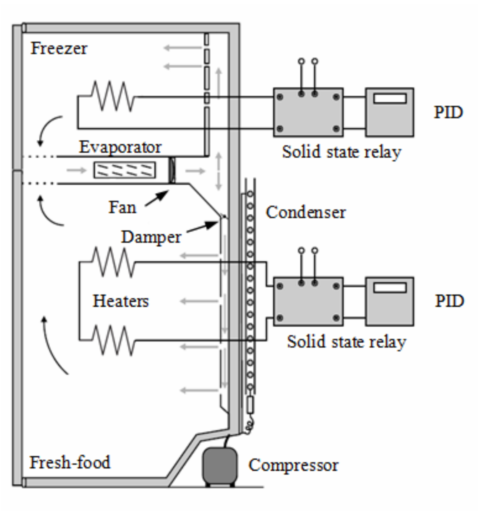

Figure 1: Schematic view of the compartment temperature controlling devices.

4. EXPERIMENTAL WORK

4.1 Climate chamber

In order to evaluate the proposed steady-state energy (SSE) test method, the refrigerator was carefully instrumented with thermocouples, and pressure and power transducers, and was tested within a climate chamber able to control the air temperature ranging from 15 to 50ºC (±0.2°C uncertainty band) and the relative humidity ranging from 40 to 95 % (±5% uncertainty band). The chamber is comprised of a cooling system (compressor, condenser, expansion device and evaporator), an air circulation system (fans and damper), and a heating system comprised of electrical heaters and a humidifier (i.e. an electrical heater immersed in a water reservoir). The air temperatures are registered by four thermocouples positioned within the chamber ceiling, while the relative humidity is measured by a sensor located at the ceiling geometrical center. A schematic view is shown in Fig. 2.

The air temperature is controlled by a PID-controlled electrical heater and a cooling system that runs continuously. The relative humidity is also controlled by a PID device which drives the humidifier heater according to the signal provided by the relative humidity transducer. According to the recommendations of ISO 15502 (2005), the air velocity inside the chamber should not exceed 0.25 m/s. Tests were performed following the SSE approach. The temperatures at several points along the refrigeration loop were registered by T-type thermocouples with an uncertainty of ±0.2 °C. For the SSE and RHL tests, the refrigerator was instrumented with four 15-W electrical heaters in the freezer compartment and eight 15-W heaters in the fresh-food compartment, as illustrated in Fig. 3.a. In addition to the proposed tests, standardized ISO energy tests were also carried out to establish a baseline for comparison and validation. In this case, the refrigerator was instrumented with loading packages, as depicted in Fig. 3.b, according to the loading map provided by the manufacturer. The compressor suction and discharge pressures were measured by two strain-gage absolute-pressure transducers positioned at the compressor suction and discharge ports, with operating ranges of 0 to 10 bar and from 0 to 20 bar, respectively. Electrical parameters, such as voltage, current and power, were measured by transducers with an uncertainty of ±0.1% (full scale). An HP Agilent 7500 system was used for data acquisition and processing.

4.2 Reverse Heat Leakage Tests

The RHL tests (Gonçalves *et al*., 2000, Gonçalves *et al*., 2011) were carried out with the refrigerator placed inside the climate chamber at a predefined ambient temperature. The cooling system was switched off. The compartments were then heated using the PID-driven electric heaters to temperatures higher than that of the surrounding air. In total, four tests were conducted, each one with different compartment temperatures, as summarized in Table 2. The freezer and fresh-food thermal conductances were obtained from a best-fit using the data available from the RHL tests and also the following energy balance over the refrigerated compartment:

$$UA_{fz}(T_a - T_{fz}) + UA_{ff}(T_a - T_{ff}) - (W_{fz} + W_{ff} + W_{e,f}) = 0 \tag{7}$$

The figures obtained for the freezer and fresh-food conductances were 0.64 and 1.30 W/K, respectively.

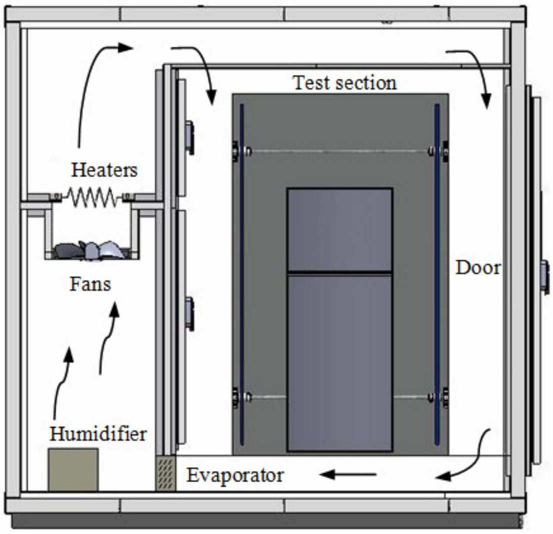

Figure 2: Schematic view of the climate chamber.

Figure 3: Refrigerator instrumentation: (a) SSE and (b) ISO

Table 2: Reverse heat leakage test data

Test	#1	#2	#3	#4
Fresh-food temperature, ºC	31.3	35.0	39.4	43.6
Freezer temperature, ºC	39.1	47.7	52.8	55.2
Ambient temperature, ºC	24.9	24.9	24.9	24.9
Fresh-food heater, W	0.0	1.4	8.2	17.5
Freezer heater, W	11.0	20.0	22.3	19.9
Fan power, W	6.3	6.3	6.2	6.2

5. RESULTS

Both SSE and ISO energy tests were carried out with three distinct refrigerator configurations, the original and two others in which the condenser had 50 and 75% of its external heat transfer surface covered by a 10-mm thick insulating blanket, as shown in Fig. 4. Since the product was designed for the Latin America region (T-class), the tests were conducted with an ambient temperature of 32ºC and the compartments were kept at -18ºC (freezer) and 5ºC (fresh-food). For the standardized ISO tests, the freezer was loaded with packages, whereas the SSE tests were conducted with no loading. The results are summarized in Tables 3 to 5, and also in Fig. 5.

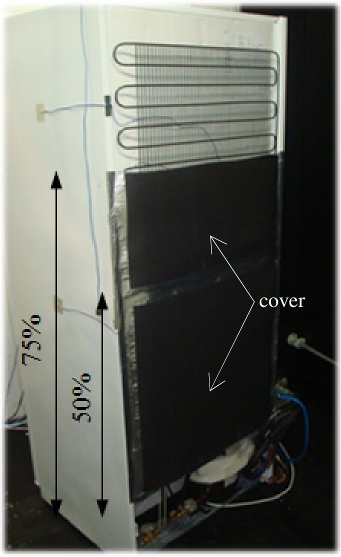

Figure 4: Photograph of the condenser covering.

Table 3: Top-mount results: original configuration (no covering)

	ISO	SSE	Difference, %
Thermal load, W	-	75.2	-
Cooling capacity, W	-	106.8	-
Coefficient of performance, -	-	1.04	-
Runtime, %	71.4	68.0	4.8
Energy consumption, kWh/month	54.56	50.34	7.7

Table 4: Top-mount results: 50% covering

	ISO	SSE	Difference, %
Thermal load, W	-	75.2	-
Cooling capacity, W	-	103.5	-
Coefficient of performance, -	-	0.99	-
Runtime, %	74.4	70.3	5.5
Energy consumption, kWh/month	56.15	52.94	5.7

Table 5: Top-mount results: 75% covering

	ISO	SSE	Difference, %
Thermal load, W	-	75.1	-
Cooling capacity, W	-	102.2	-
Coefficient of performance, -	-	0.97	-
Runtime, %	75.4	71.2	5.6
Energy consumption, kWh/month	57.4	54.13	5.7

As can be seen, the proposed method provides figures reasonably close to those obtained in the ISO energy test, with differences around the 5% threshold. Figure 5 shows that despite the absolute differences between the values obtained using both the SSE and ISO test methods, the proposed methodology followed closely the experimental trends observed with the ISO methodology. The differences found might be related to the occurrence of a defrost cycle, which increases the energy consumption in the ISO tests, and also to the presence of loading packages, that not only increases the thermal inertia of the freezer compartment but also decreases the air flow rate by increasing the air-side pressure drop.

To verify the applicability of the proposed methodology to other refrigerating appliances, two other refrigerators were tested: (i) a 340-liter bottom-mount frost-free refrigerator with forced convection on both evaporator and condenser coils; and (ii) a 450-liter direct-cool cycle-defrost top-mount unit with buoyant airflows in both the condenser and the evaporator. Reverse heat leakage tests were carried out with both refrigerators.

For the bottom-mount, thermal conductances of 0.53 and 1.35 W/K were found for the freezer and fresh-food compartments, respectively; whereas for the direct-cool, conductances of 0.46 and 1.53 W/K were obtained for the freezer and fresh-food, respectively.

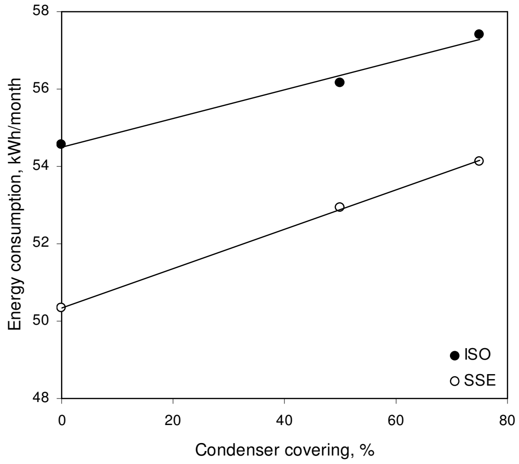

Figure 5: Energy consumption as a function of the condenser covering

Again, both SSE and ISO energy tests were conducted according to the temperatures recommended for T-class products. In this analysis, a single ISO test and a single SSE test were performed for each refrigerator. The results are summarized in Tables 6 and 7. For the bottom-mount unit, the differences observed for the compressor runtime and energy consumption are lower than 1 %, a figure within the experimental uncertainty band. The results obtained for the direct-cool unit showed a higher discrepancy between the ISO and SSE test methods, which is probably due to the approximation used in eq. (3), which provides poorer results in the case of longer transients typical of refrigerators with natural draft heat exchangers.

Table 6: Bottom-mount results

	ISO	SSE	Difference, %
Thermal load, W	-	51.9	-
Cooling capacity, W	-	126.8	-
Coefficient of performance, -	-	1.01	-
Runtime, %	39.8	40.9	2.8
Energy consumption, kWh/month	37.5	37.2	-0.9

The time required to carry out the SSE test was approximately 8 hours, while at least 48 hours were required for each ISO test, *i.e.* the standard test is 12 times longer than the proposed approach. In addition, the steady-state test allowed the calculation of the cooling capacity, the thermal load and the system COP, parameters that are not usually quantified during the ISO tests.

Table 7: Direct-cool results

	ISO	SSE	Difference, %
Thermal load, W	-	64.6	-
Cooling capacity, W	-	117.9	-
Coefficient of performance, -	-	1.03	-
Runtime, %	55.6	54.8	1.4
Energy consumption, kWh/month	53.3	45.2	15.2

6. CONCLUSIONS

A new test method to assess the energy consumption of household refrigerators was proposed. Such an approach has the advantage of requiring a shorter test period compared to the standardized energy test procedures. In addition, it allows the calculation of important design parameters, such as the thermal load, the cooling capacity and the refrigerator COP, which are not considered in the standardized test procedures.

In the case of the frost-free refrigerating appliance, the results of the proposed steady-state energy tests were compared to those obtained with the ISO energy tests and it was observed that the former followed closely the trends observed for the latter. These results were confirmed for a bottom-mount frost-free refrigerator with a forced-air condenser, with differences not exceeding 1%. However, in the case of the direct-cool refrigerator with natural draft condenser and evaporator was evaluated, the energy consumption discrepancy between the SSE and ISO test approaches was higher than 15%, which is speculated to be due to the limitations of eq. (3) when applied to refrigerators that undergo longer transients.

Although the proposed methodology does not predict exactly the ISO test results, it follows closely the trends, and is at least 12 times faster than the standardized approach, being therefore more suitable for engineering investigations in the proof-of-concept phase, such as component matching and capillary tube / refrigerant charge adjustments, which are more concerned with differences between modified and baseline values than with the energy consumption labeling and product approval.

It should be emphasized that the proposed methodology is not intended to replace the standardized tests which are mandatory for the approval of a product before being placed on the market, but rather to reduce the number of tests needed during the product development process.

NOMENCLATURE

COP	Coefficient of performance	(–)
EC	Energy consumption	(kWh/month)
Q_t	Thermal load	(W)
Q_e	Cooling capacity	(W)
t	Time	(h)
T	Temperature	(ºC)
UA	Thermal conductance	(W/K)
W	Power consumption	(W)
τ	Runtime	(–)

Subscripts

a	ambient
c	compressor
e	evaporator
f	fan
ff	fresh-food
fz	freezer

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