Air Infiltration: a Key Issue on Household Refrigerators

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ABSTRACT: One important vector for a sustainable growth of our planet is the air ventilation due to the large amounts of energy spent. When speaking about ventilation, the main thought is concerned with buildings. However, there is one more important sector, besides the building one, where a special attention is due: the refrigeration sector. The cooling of the outside air due to the air infiltration on refrigeration stores can consume also a large amount of energy. Read these notes carefully all the way through and follow them as precisely as possible. In this work several measurements were carried out on a common household refrigerator in order to find the air exchange rate trough the magnetic seal of the door. Tests were realized with a new and an old door seal. The main conclusion to withdraw is that the air infiltration rate on the refrigerator increases very fast as it becomes old, increasing in that way the energy consumption of the refrigerator.

Keywords: air infiltration, household refrigerator, air exchange rate, sustainability.

NOMENCLATURE

c	Tracer gas concentration [ppm]
c_0	Initial tracer gas concentration [ppm]
c_{atm}	Outside tracer gas concentration [ppm]
c_p	Specific heat [kJ/kgK]
I	Air exchange rate [h^{-1}]
$\dot{m}$	Mass flow rate [$kg.s^{-1}$]
q	Tracer gas mass [ppm]
t	Time [s]
T_{ext}	Outside air temperature [K]
T_{int}	Inside air temperature [K]
V	Volume [m^3]
$\dot{V}$	Volume flow rate [$m^3.s^{-1}$]
ρ	Density [kg/m^3]

1. INTRODUCTION

One important vector for a sustainable growth of our planet is the air ventilation, in the three different mechanics it can be presented: air infiltration, natural ventilation and mechanical ventilation. When speaking about ventilation, the main thought is concerned with buildings, and its importance relies on the fact that it is needed good indoor air quality. This air exchanges are responsible for a large parcel of the building energetic bill, either for heating or cooling the outside air either to move it with a fan [1-4].

However, there is one more important sector, besides the building one, where a special attention is due: the refrigeration sector. In all refrigeration stores, household refrigerators or freezers there is an air exchange between the outside air and inside air, this last one usually at much lower temperatures than the ones found in buildings. So the cooling of the outside air can consume also a large amount of energy mainly due to the temperature difference between the outside and inside air. In this work several measurements were carried out on a common household refrigerator in order to find the air exchange rate trough the magnetic seal of the door. The measurements were carried out with the tracer gas technique. Tests were realized with a new and an old door seal. The main conclusion to withdraw is that the air infiltration rate on the refrigerator increases very fast as it becomes old, increasing in that way the energy consumption of the refrigerator.

2. TRACER GAS TECHNIQUE

This method consist in the introduction of certain quantity of a known gas in the space where the air infiltration is to be measured – the tracer gas – and measuring the tracer concentration with time with an appropriate gas analyzer. Once known the tracer concentration evolution it is possible to evaluate the air infiltration rate after appropriate mathematical analysis, [5, 6]. For that it is supposed that the space under study behaves as a single zone, with a uniform tracer gas concentration in all the space, Fig.1.

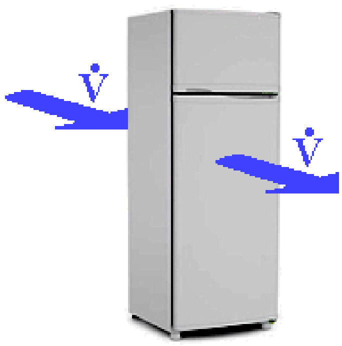

Figure 1: Schematic representation of a single zone.

A tracer gas balance of the space results in the following equation:

$$q.dt - (c - c_{atm}).I.V.dt = \left(\frac{dc}{dt}\right).dt.V$$

where I is the air exchange rate (Air Changes per Hour – ACH):

$$I = \frac{V}{\dot{V}}$$

Reorganizing the parcels, it is possible to get the non homogenous first order non linear equation:

$$\frac{dc}{dt} + I.c = I.c_{atm} + \frac{q}{V}$$

After resolution, and taking logarithms, it is possible to get the air infiltration rate trough the measurements of the concentration:

$$I = \frac{1}{t}.\ln\left(\frac{c_0}{c}\right)$$

As can be seen only two measurements of the tracer concentration (c_0 and c for a certain time interval) would be enough to calculate I for the space. However in this case the error in the evaluation of I should be large. So it is usual to measure several values of the tracer concentration at regular time intervals. These values plotted in a graph ln(c) versus time lies around a straight line, which the absolute value of its slope is equal to the air exchange rate of the space, [7]. The visualization of the graph enables also to verify if the air infiltration rate during the test is steady (only a straight line) or unsteady (two or more slopes). Fig.2 represents one of the tests carried out on one refrigerator.

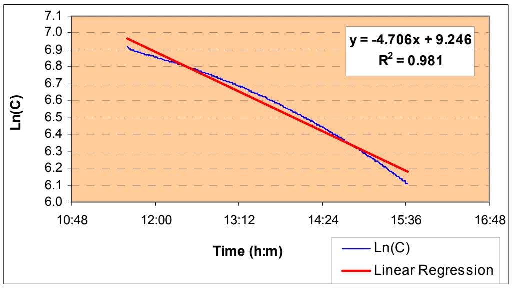

Figure 2: Example of a plot of ln(c) versus time.

3. TEST FACILITIES

In order to analyze the influence of the magnetic seals of the door, it was used a commercial double door domestic freezer, with one refrigeration compartment (internal volume of 0.22 m^3) and a freezer compartment (internal volume of 0.067 m^3), [8]. Two magnetic seals of the refrigeration compartment were available, one new, and the other one too much older. The freezer cabin had always the same seal. The tests were realized with one seal which afterwards was replaced by the other one.

Thermocouples previously calibrated were located inside both compartments and outside in order to evaluate the inside and outside air temperatures. All thermocouples were connected to a data acquisition system that read all temperatures in 20 seconds intervals.

At the same time the compressor power and energy consumption were measured with a digital energy analyzer, previously calibrated. The results were recorded in a data logger, [9], for further analysis

Sulphur hexafluoride, SF_6, was the only tracer gas used in the tests, [10]. The tracer flow off from the pressurized bottle to the tracer dozer, trough a very sensitive low pressure regulator and was injected to both compartments until an internal average concentration of 1000 ppm was reached inside. After that, the tracer injection was cut off and samples of the internal air refrigerator were acquired. The tracer gas concentration was measured by using a photo acoustic multi-gas analyzer, model 1312, manufactured by INNOVA (former Brüel & Kjær) [11].

The duration of the tests realized was variable in time, but the values of the air infiltration rate were taken on an hour basis.

4. RESULTS

The results obtained with the new door magnetic seal are shown on Figure 3 (outside and inside air temperatures) and 4 (tracer gas evolution) for the refrigeration cabin and on Figure 5 (outside and inside air temperatures) and 6 (tracer gas evolution) for the freezer cabin.

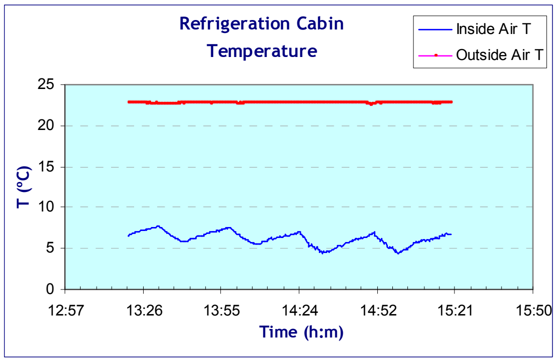

Figure 3: Outside and inside air temperatures of the refrigeration cabin (new seal).

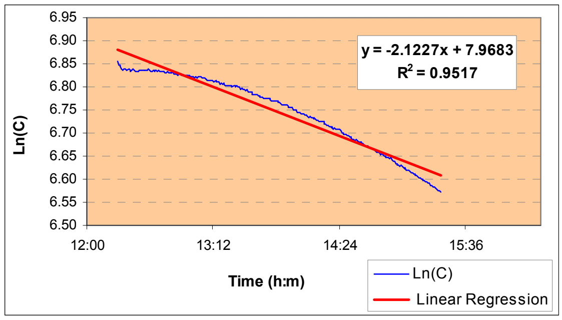

Figure 4: Tracer gas evolution of the refrigeration cabin (new seal).

Fig. 7 shows the compressor amperage and Fig.8 the power consumption of the compressor. Once completed all these tests, the new seal was substituted by an older one on the refrigeration cabin, and the experiences were repeated again. On Figs 9 and 10 are shown respectively the tracer gas evolution on the refrigeration and freezer compartment with the old seals.

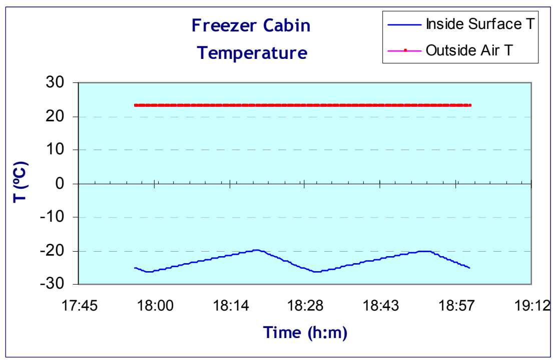

Figure 5: Outside and inside air temperatures of the freezer cabin (new seal).

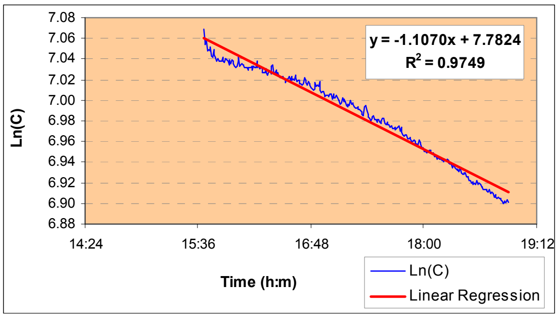

Figure 6: Tracer gas evolution of the freezer cabin (new seal).

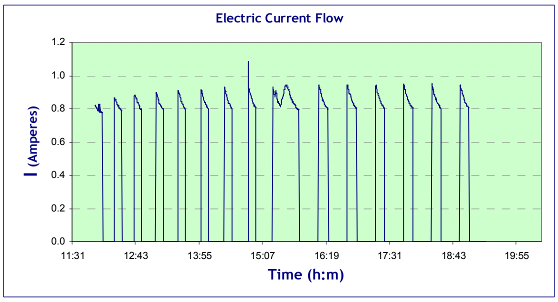

Figure 7: Compressor amperage (new seal).

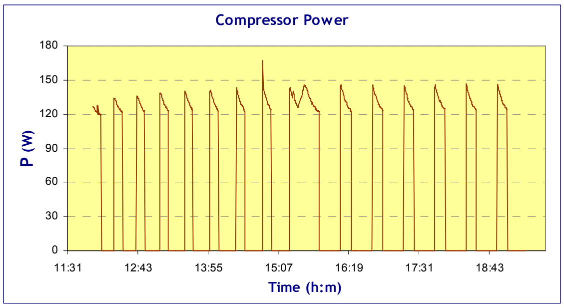

Figure 8: Compressor power (new seal) (new seal).

As can be seen in figures 4, 6, 9 and 10 the slope of tracer decay in the refrigeration cabin is larger than in the freezer cabin which means that the air infiltration rate is also larger.

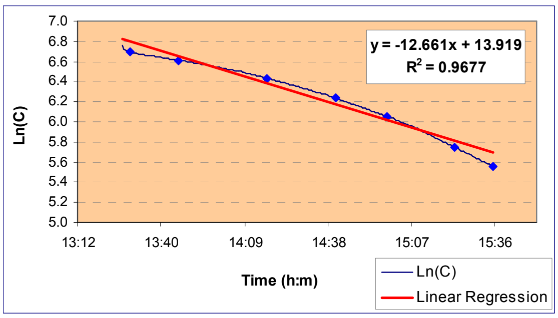

Figure 9: Tracer gas evolution of the refrigeration cabin (old seal).

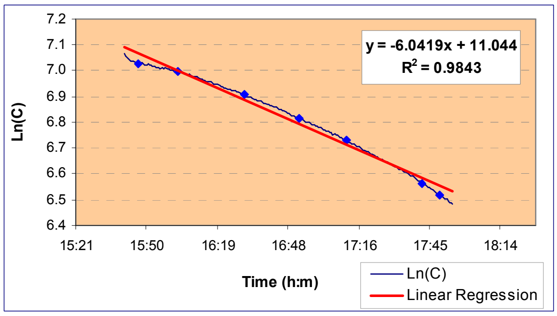

Figure 10: Tracer gas evolution of the freezer cabin (old seal).

This is an expected result because the pressure inside the last cabin is lower, and so, the magnetic seal is more compressed minimizing the air exchange.

The heat power related with the air infiltration rate is obtained through the following equation:

$$\dot{Q} = \dot{m}\, c_p \left(T_{ext} - T_{\text{int}}\right)$$

where:

$$\dot{m} = \dot{V}\, \rho = V * I * \rho$$

Table I presents all the numerical results regarding the air infiltration (including the correlation coefficient of the best fit line to the concentration evolution) while Table II shows the results of the electrical consumption of the compressor.

The first conclusion to withdraw from table I and II is that the air infiltration rate is always larger on the refrigerator cabin when compared with the freezer one, almost double, either with the new and old seals.

Table I: Power and energy associated to I on one hour basis.

Seal	Cabin	I	R^2	$\dot{Q}$	Q	Total Q
		(ACH)	(°C)	(W)	(Wh)	(Wh)
New	Refrigerator	2,1	0,95	2,35	2,35	
	Freezer	1,1	0,97	0,93	0,93	3,28
Old	Refrigerator	12,7	0,97	14,20	14,20	
	Freezer	6,7	0,98	5,80	5,80	19,90
Increase (%)	Refrigerator	505			504	
	Freezer	509			524	506

Table II: Electrical consumption associated to I on one hour basis.

Seal	Compressor power (W)	Compressor Energy (Wh)	% of energy to I
New	45,5	45,5	7,1
Old	63,7	63,7	31,3
Increase (%)	40	40	341

This occurs because the air temperature differential between inside and outside air is larger on the freezer cabin and so the pressure differential. The consequence is that the freezer seal is much more compressed, minimizing on that way the air infiltration rate to the cabin.

The increase of the air infiltration rate due to the change of the new seals by the old ones is respectively 504% for the refrigerator cabin and 509% for the freezer compartment, which reflects on the energy consumed by the compressor that shows a total increase of 341% on the electricity consumed.

In order to have a full idea regarding how the energy consumption of the compressor is spread on the equipment (heat gains through the walls and air infiltration rate), a detailed analysis of the heat transfer rate trough the all envelope of the refrigerator was carried out. The final results are shown on Table III.

Table III: Coefficient of performance for refrigerator with new seals and old seals tests.

ENERGY USAGE (COP)					
Element			New Seals Test (Wh)	Old Seals Test (Wh)	difference (per cent) (%)
$\dot{W}_{Comp}$	Power consumed by the compressor		45.5	63.7	40
$\dot{Q}_{useful}$	Useful ratio of heat supplied	Infiltration	3.28	19.9	506
		Heat transfer through walls	89.0	87.7	-1.5
$COP = \lvert\dot{Q}_{useful}\rvert / \dot{W}_{comp}$		Coefficient Of Performance	2.03	1.69	-17

As can also be seen, the total energy related to the air infiltration is 3.28Wh with the new seals and 19.9Wh with old seals. This difference represents a reduction of 8.2Wh on the energy consumed by the compressor, which seems very small quantity. However, and as follows, a simple exercise can be done regarding the theory of small numbers.

Taking in account that the world population in 2005 was about 6.5 billions, [15] and, on average, assuming that there are four members per family and only 50% of the families have refrigerators similar to the one tested, there will exist on earth 812.5 millions of refrigerators. Assuming now that in one fifth of them the seals are not in good conditions, the electrical energy that could be saved if the seals were replaced by new ones would be around 5.8 GWh/year in all world. Now this is a huge number, with all the consequences related to the fossil fuels depletion and green house effect due to the CO_2 emissions associated to the electricity production. Taking in account that, on average, there is a production of 0.6 kg of CO_2 per kWh as final energy, the total emissions of CO_2 to the environment could be reduced by 3.5 billions of tons per year.

5. CONCLUSIONS

In the natural use of refrigerators of almost all kinds, the magnetic door seals deteriorates with time either to the loss of capacity of the magnetic band either to the new cracks in the rubber and even to negligence of the users. This implies a larger air infiltration rate to the cabins and, as a direct consequence, a large energy consumption to overcome this increase.

In this work it was quantified the influence of the magnetic door seal conditions upon the air infiltration rate in a domestic double door refrigerator as well as its overall heat balance.

The first conclusion to withdraw from the tests is that the refrigerator cabin has almost twice the value of the air infiltration rate when compared with the freezer cabin (due to the much lower temperatures in this last cabin). So, special care must be dedicated to the seals of the refrigerators, where the temperatures are positive.

A second conclusion is that the increase on the air infiltration rate due to the deterioration of magnetic seals of the doors is about 505% for the equipment tested, which reflects on the energy consumed by the compressor that shows a total increase of 341% on the electricity consumed. When the seals are new, 3.6% of the energy used to run the compressor is spent on the air infiltration and 96.4% on heat gains through the walls, while when they become leaker these percentages become respectively 18.5% and 81.5%. As a consequence, there is a significant increase in the compressor energy consumption which implies higher running cost as well worst environmental implications.

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