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THERMAL IMPROVEMENTS IN HOUSEHOLD REFRIGERATORS

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ABSTRACT

In this paper it is described the thermal behaviour of available commercial domestic refrigerators-freezers. The freezers were monitored with thermocouples and with one electrical meter connected to the hermetic compressor. The results were acquired and stored in a data logger. With the results obtained in the experimental apparatus, it was used an available commercial code in order to simulate the air temperature distribution and air velocities inside the freezer. Results from several independent improvements done on an experimental refrigerator and from simulations showed that they improve the thermal behaviour of this kind of freezers, becoming energetically more efficient.

Keywords: household refrigerators, radiation shields, air temperature and velocities distribution, magnetic seals

INTRODUCTION

Since long time ago that the commercial domestic refrigerators-freezers have been built in similar way, besides minor esthetic aspects and of course making now use of the new zero depletion ozone refrigerants. Thermodynamically speaking, all refrigerators are based on conventional vapor compression refrigeration cycles. Usually the refrigerant after adiabatic expansion in a capillary tube or other type of expansion valve flows through the freezer evaporator and then trough the refrigerator evaporator. After heat gain in both spaces, the refrigerant effect, the refrigerant is compressed and then releases the accumulated energy in the condenser, usually of a natural air cooled type, closing in that way the refrigeration cycle (Afonso, 2012).

Regarding the position of the four typical equipment's of the vapor compression refrigeration cycle (evaporator, compressor, expansion valve and condenser), they are placed almost in the same position in all refrigerators-freezers. While the compressor is located in a recess at the bottom of the refrigerator the natural air cooled condenser is located in the rear wall of the refrigerator.

Previous experimental work already done had shown that the outside surface temperature of the rear wall were the condenser is located as well as the walls close to the compressor have a much higher temperature than the outside air with witch all freezer-refrigerator surfaces exchanges heat. This is due to the heat release from the condenser and from the compressor. This causes larger heat gains to the freezer-refrigerator in those walls when compared with the others (Afonso et al, 2003).

In order to evaluate the effect of the heat release of the condenser and the compressor in the thermal behavior of this kind of equipment, tests have been done in a conventional available refrigerator-freezer. Modifications in the rear wall and in the recess walls where the compressor is located in the refrigerator-freezer have been carried out separately in order to evaluate the individual influence of each one. In this work the modifications simply consists in placing a radiation shield composed of a sheet of aluminum foil over those walls. After the evaluation of the individual influence of each one of the surfaces in the internal air temperatures and energy consumption of the compressor a final test was done with the radiation shield placed simultaneously in the rear wall and in the recess walls of the compressor. Also, in a separate test, the recess wall of the compressor was mechanical ventilated.

Another problem that arises when the refrigerators become older is the increase in leakage through the magnetic seals around the doors. In order to analyze their influence two magnetic seals were tested: one new and another one old.

The refrigerator-freezer was monitored with thermocouples previously calibrated and with an energy meter. All the measured values were recorded in a data logger, for further analysis. The tests were conducted in a laboratory in Porto University.

METODOLOGY

The freezer, Fig.1a), works with a standard vapor compression cycle with 0.13 kg of R-134a as refrigerant.

The refrigerant after adiabatic expansion through the capillary tube enters the upper cabinet freezer (negative air temperatures) and then flows to the refrigerator (positive air temperatures). The cycle is closed with the refrigerant flowing through the hermetic compressor sited at the bottom of the refrigerator and after through the natural convection air-cooled condenser. The compressor has a nominal current of 0.77A and a nominal voltage of 220V. The net inside volume is 224 l.

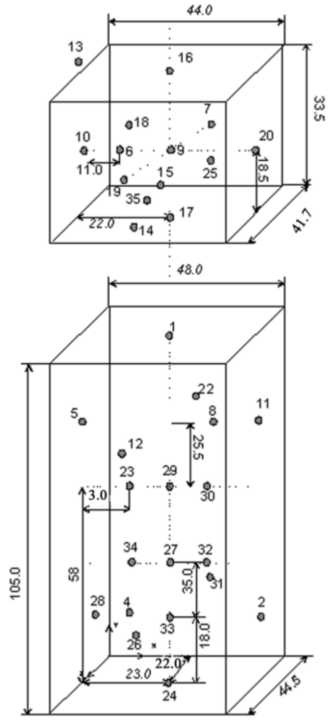
The double door refrigerator–freezer was monitored with thermocouples type T located in several points of the internal surfaces, outside surfaces, inside air in both cabinets (at three different levels) and outside air, numbered as shown in Fig. 1b). This location of the thermocouples enables to measure all the spatial inside surface temperatures as well as the inside air temperatures. For the test with the aluminum foil, three additional thermocouples, nº 15, 18 and 25 (not shown in fig.2) where placed on the inside surface of it. All thermocouples were connected to a data acquisition system that read all temperatures at 20 seconds intervals. At the same time the compressor power and energy consumption was measured and the results were kept in a conventional PC for later analysis.

The radiation shield used on the tests was of the type of aluminum foil with a thickness of 3µ ± 5%. The emissivity (value given by the producer), is 0.07.

Four tests were carried out: the first one with the refrigerator-freezer as it comes from the factory (reference test) the second one with the radiation shield on the rear wall, a third one with the radiation shield in the recess of the compressor and finally a fourth one with the radiation shield on the rear wall and on the recess Only the results obtained in refrigeration cabin will be presented.

ORIGINAL REFRIGERATOR

The temperature evolution measured with the thermocouples mentioned in the last section is shown in Fig. 2 for the refrigerator.



a) The refrigerator b) – Location of the thermocouples

Fig 1. View of the refrigerator/ freezer

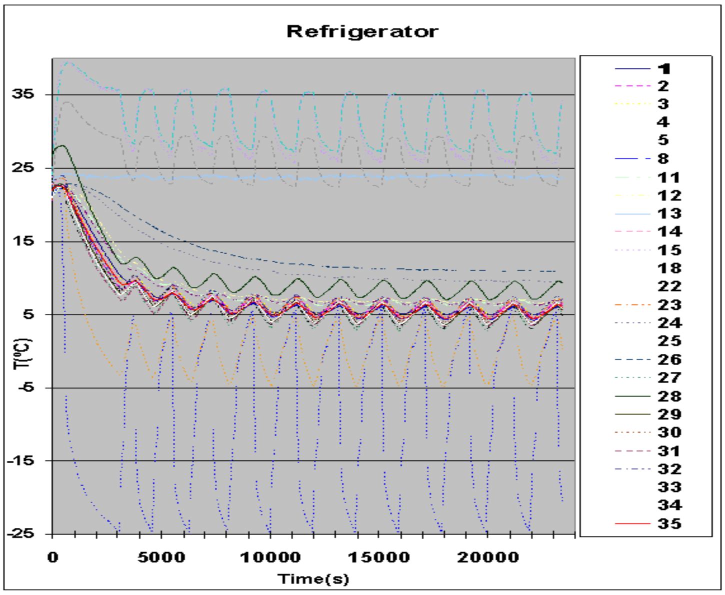


Fig.2 Temperature evolutions in the refrigerator.

Generally speaking, all the measured temperatures of the inside air follow the compressor working cycle (set of ten lines almost superimposed in the middle of the figure, third lines from the bottom of the figure)

The transient regime took approximately 51 minutes from the starting point in which the freezer was in thermal equilibrium with the outside environment until the minimum surface temperature of the evaporator was reached and the compressor stopped working. From figure 3 it can also be seen that the compressor works between a maximum surface evaporator temperature of 5.5ºC and a minimum of –24.5ºC, and stopped working in the reverse direction of the so mentioned temperatures (thermocouple 4 – bottom curve of the graph). The entire cycle takes about 35 minutes, being approximately 42% of the time spend with the compressor working and the other 58% with the compressor stopped, Table 1.

Table 1 Compressor cycle operation for different locations of the radiation shield.

Radiation shield	Cycle time (min.)	(%) stopped	(%) running	Time to reach steady state (min.)
Without	33.3	61.0	39.0	51
Rear wall	35,3	61.3	38.6	42
Comp. recess	34.3	62.1	37.8	42
Rear wall+comp. recess	36.3	62.4	37.6	52

RADIATION SHIELD ONLY ON THE REAR WALL, ONLY ON THE COMPRESSOR RECESS AND ON BOTH SURFACES OF THE REFRIGERATOR

Energy efficiency is improved by application of a radiation shield. Several possibilities were investigated in the same way as for the refrigerator/freezer system without radiation shield. Tests were carried out independently, one by one. The aluminium foil was glued first in the rear wall of the refrigerator-freezer (the three thermocouples 15, 18 and 25 where then covered by it), then in the compressor recess and finally on both surfaces. The going of the temperature evolutions in the three tests are identical to figure 3, except for the temperature limits and cycle times. The main results are shown in Table 1 and 2.

Table 2 Minimum and maximum inside air temperature at different heights in the refrigerator (ºC) for different locations of the radiation shield (rs).

Height (cm)	Without rs	Rear wall with rs	Recess with rs	Real wall+recess with rs
83.5	4.5/6.6	4.3/6.9	4.1/5.9	3.9/6.3
58	3.8/7.0	2.6/6.9	3.7/6.3	2.5/5.2
53	2.9/7.4	1.8/6.3	2.5/6.1	1.1/5.1
35	3.1/6.5	2.3/5.7	2.2/5.3	1.8/5.6
$T_{aver.}$	3.6/6.9	2.8/6.5	3.1/5.9	2.3/5.5
σ	0.6/0.35	0.93/0.49	0.79/0.37	1.0/0.47

As it can be seen in these three cases the cycle time is longer when compared with the refrigerator-freezer in its original situation due to the increased time when the compressor not works. It can also be seen that the compressor running time is lower. Regarding the time to reach the steady state no conclusion can be withdraw from the tests as there is a significant reduction in time when the radiation shield is located only in the rear wall and only in the compressor recess (9 minutes less than the original situation) and there is an increase in time when the radiation shield is located over both surfaces (1 minute more than the original situation).

Regarding the air temperatures inside the refrigerator it can be seen that the minimum air temperatures decreases from the top to the bottom of the refrigerator, except for the lower level (located at a height of 35 cm) that is on average slightly higher than the immediate upper level (height of 53 cm). As these air temperatures are reached when the compressor did not worked, this can be explained by the cooling effect of the much colder evaporator. It can also be seen that the minimum inside air temperatures are reached when the radiation shield is mounted on the rear wall and compressor recess. Thus, it can be concluded that the radiation shield has a positive effect on the air temperatures inside the freezer system.

Regarding the maximum inside air temperatures inside the refrigerator (when the compressor is about to start running) it can be seen that on average they increase from bottom to the top of the refrigerator. This is expected due to the heat gain through the walls. Again, the radiation shields located in the rear wall of the refrigerator and in the compressor recess have an effect of lowering on average the inside air temperatures.

ENERGY CONSUMPTION

In spite of a slight decrease in percentage of the running time of the compressor with the location of the radiation shield in all the rear side of the refrigerator-freezer, the energy consumption of the compressor is almost constant, about 0.031 kWh per cycle in all tests. This may be due to the control thermostat that is located in the mid height of the refrigerator where the temperatures are higher than in the bottom of the refrigerator. Thus, changing the placement of the thermostat could contribute to a decrease in the energy consumption of the compressor.

FORCED AIR VENTILATION IN THE COMPRESSOR RECESS

As said, another different test was carried out with the aim to decrease the relative high temperatures due to the effect of heat generated during the compressor operation and, in that way to reduce the energy consumption of the entire system (Freitas and Diegues, 2007). It consists in ventilating with a small fan the base of the same refrigerator where the compressor seats. For that purpose a wooden plenum with a fan was built on the base of the refrigerator as seen in Fig.3a) and the air path through it is shown in Fig. 3b).

The fan could run at full velocity (100%), at half velocity (50%) or not running (0%). In that way several tests were done:

- Refrigerator without internal load:

  Test #1: fan not running

  Test #3: full velocity

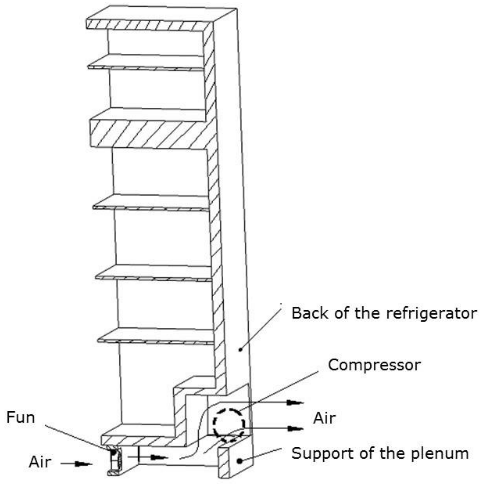
  Test #4; half velocity

- Refrigerator with internal load:

  Test #2: fan not running

  Test #5: full velocity

Test #6; half velocity



a) Plenum b) Air path through the plenum

Fig.3 View of the plenum and air path.

Table 3 the amounts of energy that can be saved by this modification per refrigerator and per year as well as the reduction of CO_2 emission to the environment. This account was done with the energy mix in Portugal, i.e., the emissions to the environment per kWh electricity produced being around 0.47 kgCO_2. Now, as can be seen, there are savings in all tests, regarding the global electricity consumption and the correspondent decrease in emissions. This means that the technology proposed is totally valid.

Table 3 Energy saved per refrigerator and per year and the reduction of CO_2 emission to the environment.

TEST	Cycling time [h]	Compressor running time [h]	Fan off time [h]	Savings per cycle [Wh]	Annual savings [kWh]	CO_2 emissions reduction [kgCO_2]
#1	0.483	0.161	-	-	-	-
#3	0.483	0.156	0.328	0.492	9	4.2
#4	0.456	0.139	0.317	0.452	8.6	4
#2	0.467	0.161	-	-	-	-
#5	0.461	0.161	0.300	0.429	8	3.8
#6	0.444	0.156	0.289	0.396	7.7	3.6

Looking to table 3, it seems that the obtained savings values are negligible, and in fact they are per refrigerator. But the product of small numbers multiplied by extremely large ones is full applicable here, (Warhaft, 1997). Given that the probable number of domestic refrigerators in the world is around 1000 million, (Bulletin of the IIR, 2002), it is possible to calculate the global new savings in energy consumption and reduction of CO_2 emissions to the environment if all the household refrigerators similar to one tested in this work were equipped with this proposed system, Table 4. As can be seen, the numbers are now impressive.

Table 4 Annual energy savings and CO_2 emissions reduction for all domestic household refrigerators in the world.

TEST	Annual savings [MWh.10^3]	CO_2 emissions reduction [tons CO_2.10^3]
#1	-	-
#3	9000	4200
#4	8600	4000
#2	-	-
#5	8000	3800
#6	7700	3600

NEW VERSUS OLD SEALS

The influence of the magnetic seals leakage upon the compressor power consumption will be analyzed. The tests were realized with one new seal which afterwards was replaced by an older one. For that the tracer gas technique was used to measure the air infiltration rate in the refrigerator (Afonso, 2013). It was empty during all the tests.

Table 5 presents all the numerical results regarding the air infiltration (including the correlation coefficient of the best fit line to the concentration evolution) while Table 6 shows the results of the electrical consumption of the compressor.

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:

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

The first conclusion to withdraw from table 1 and 2 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. 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.

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 (for a COP of 2.03 evaluated as shown on Table 9), 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 billion, [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 greenhouse effect due to the CO2 emissions associated to the electricity production. Taking in account that, on average, there is a production of 0.6 kg of CO2 per kWh as final energy, the total emissions of CO2 to the environment could be reduced by 3.5 billions of tons per year.

Table 5 Power and energy associated to I on one hour basis.

Seal	Cabin	I (ACH)	R^2 (°C)	$\dot{Q}$ (W)	Q (Wh)	Total Q (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 6 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

CONCLUSION

In this work it was shown that with minor modifications in the available commercial refrigerator-freezers it is possible to have a better performance of them. These modifications simply consist in covering the external rear wall of the refrigerator and the compressor recess wall with a sheet of aluminum foil avoiding in that way the radiation heat transfer from the condenser and the compressor to the external surfaces of the refrigerator.

Results have shown that when those surfaces are cover with a sheet of aluminum foil there is a significant decrease in the inside air temperatures of the refrigerator and of the freezer.

With a proper location of the refrigerator thermostat this can contribute to a lower energy consumption of the compressor.

Another technique used consists to build a plenum with a blowing fan underneath the refrigerator to mechanically ventilate its base, where the compressor is seated, and where the temperatures of the external surfaces are higher when compared with the other surfaces of the envelope of the refrigerator. Measurement of the temperatures in several points of inside and outside surfaces as well as of the internal air with and without the ventilation showed that is a decrease of the temperature difference across the mentioned walls with the proposed technique. As a direct consequence the heat transfer to the inside of the refrigerator will diminish too, leading to a decrease of the compression energy. The power and energy consumption of all system, compressor and fan, were measured and it was possible to conclude that there is a global saving in the energy consumption with this solution. This leads to a direct decrease of the CO_2 emissions to the environment.

Another tests done consist to see the influence of the magnetic door seals (new or olds) in the energy consumed by the refrigerator. The old ones 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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