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STUDY OF DOMESTIC REFRIGERATORS' COMPRESSORS DEGRADATION AND ENVIRONMENTAL AND FINANCIAL IMPACTS DUE TO ITS EFFICIENCY LOSS OVER TIME

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Abstract. *The normal operation of domestic refrigerator's compressors induce wear, which are intensified by time and are verified by gaps, metal particles diluted in lubricant oil and, mostly, due power consumption and operation time increases. As result, financial (electric power demand increase) and environmental (emission of equivalent carbon dioxide in atmosphere) impacts are observed. Actually, Brazil has about 65 million domestic refrigerators in operation, and more than 50% of this market has over 9 years of use. This paper shows that the presence of a large amount of old equipment requires an additional electric power production of 30 TWh per year, in the country, at an over 2 billion dollars additional cost. Furthermore, equivalent CO2 emissions overcome 3 million tons per year. The article presents the Brazilian's refrigerator market main characteristics, including its technological evolution; the distribution in operation time function, of the equipment in this market; domestic refrigerators compressors efficiency loss estimation, over time; and the financial and environmental impacts estimative, due to these equipment uses.*

Keywords: *efficiency loss; compressors' degradation; environmental impacts.*

1. INTRODUCTION

The power consumption of a fridge is usually estimated during the project design phase. The mathematical models considers the heat exchange that occurs in the equipment; the sort and the amount of refrigerant confined in the system; the compressors' supply and exhaust pressures, among others variables. However, these models cannot predict the power consumption increase over time, due to wear accumulation, that naturally occurs as result of equipment operation.

The compressor is the refrigerator's component in which are observed wear with more intensity and, although well-known the physical phenomena that causes its degradation, such as flooded starts, refrigerant flood back, overheating, etc., in literature, the studies correlating this degradation to the operation time are almost nonexistent. So, the mathematical models used nowadays neglects the efficiency loss and, therefore, underestimate the real consumption of the equipment and omit important financial and environmental impacts data due to refrigerator's use.

Presently, Brazil has about 65 million domestic refrigerators in operation, and more than 50% overcome 9 years of use. Kim et al (2006) observed that equipment in use time range between 2 and 7 years are energetically ideal, and concluded that a typical domestic refrigerator should be changed if its annual consumption overcomes 1.000 kWh, verified, on average, after 13 years of operation, which corresponds to more than 28% of the equipment in Brazilian market (Giuliani, 2013).

In a similar study, Januzzi (2007) estimated the electrical power financial costs and concluded that 7 years is the most suitable time to discard the refrigerator, once its consumption increase, its maintenance costs and the technological obsolescence presuppose economical disadvantages when considered a new equipment acquisition. Nevertheless, in Brazil, more than 60% of refrigerators have more than 7 years of use, so it's old and inefficient. This represents an interesting opportunity for its renewal.

Garland and Hadfield (2004) tested several unities that operates with refrigerant HFC134a, and conclude that after 11 years of operation, the efficiency loss is about 40%. Actually, in Brazil, over 3 million refrigerators operated for more than 11 years. This represents an additional annual consumption of 370 GWh, due this degradation as well as an annual spending of 26 million dollars.

Cardoso and Nogueira (2008) proposed a simple performance decreasing model, based in information provided by refrigerator's manufacturers, which considers no efficiency loss in the first five years of use and a gradual increase, which reaches 60% after 16 years of operation.

Although an extensive literature research has been done during work, it was observed that studies which relate degradation to the operation time for refrigerators are scarce in literature. Thus, this article aims to propose a relation between degradation and time of usage for fridges. Furthermore, the main characteristics of the Brazilian's refrigerator market, as well as its evolution over time, are discussed. Finally, financial and environmental impacts due to this efficiency loss are estimated.

2. BRAZILIAN FRIDGE MARKET

In order to determine the financial and environmental impacts caused by domestic refrigerators, the main characteristics of these equipment and its distribution in operation time function must be known. This section discusses the Brazilian domestic refrigerator market evolution and its future expected scenarios.

In 2011, there were 65 million domestic refrigerators operating in Brazil (IBGE, 2010) and 1,2 billion in world (EPA, 2011). Thus, the national market represents about 5% of these equipment's' international market.

Pereira (2010) estimated the evolution of the amount of operating equipment in Brazil between 1990 and 2010. In 2010, there were 61,6 million unities for 194 million people living in the country (UN, 2010), i.e., about 1 unity for each 3 people. Furthermore, in 2010, the author estimated that 97,1% of Brazilian homes had a fridge, and, in 2015, 99,5% of them will have one (IBGE, 2010). This means that, virtually, the whole population will have access to, at least, one refrigerator.

Thus, it is expected that the relation between the amount of refrigerators and the total population of the country remain constant, although an economic scenario change can affect this relation. However, if this remains, it is possible to project a future scenario for refrigerators market until 2040, when the population should reach its maximum value in Brazil, with 224 million people (UN, 2012).

The balance between input and output was always positive. However, to make estimative more precise, it is necessary to know the effective amount of equipment that entered the market and the age of those which leaved it.

Brazilian Environmental Ministry provided data about the amount of input and output equipment in the market, each year, between 1991 and 2011 (BRAZIL, 2011). Both the input and output data fluctuates from each year and do not have a defined pattern, once refrigerators' acquisition and discard is very influenced by the country's economic scenario, governmental incentive, technological advancements, among others. Figure 1 shows the refrigerator market variation in the referred period.

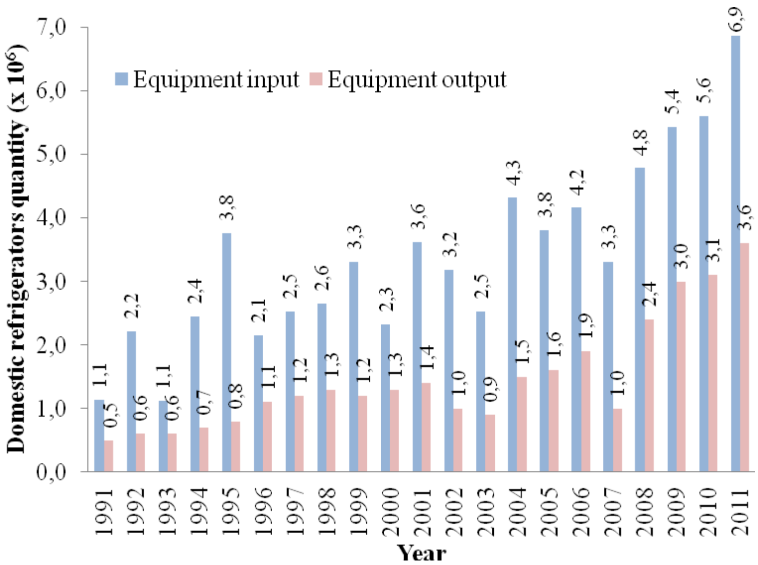

Figure 1 – Refrigerators' input and output balance, in Brazil.

Since 2004, the amount of input and output is more expressive than in previous years. This is explained by the fact that Brazil entered in an economic stability period. It is notable that in 2007 and 2008, the world financial system slumped and, thus, this reflected in Brazil's market, as observed in Fig. 1. However, there is an input and output increase tendency by the years.

In next 30 years, the Brazilian market increase rate shall be lower than the verified actually. This means that the amount of discards shall approach the amount of new refrigerators acquisition. The economic facilities and technological advancements shall stimulate the market renewal, with discards occurring each time early.

Obviously, an older equipment cause more intense impacts than a newer one. Therefore, knowing the absolute amount of discarded equipment is not enough. It is necessary to classify then in function of its operation time so the impacts estimative can be more accurate. Furthermore, this information can be used in refrigerator's market renewal strategies which can reduce environmental impacts and increase efficiency energy.

Equipment discard is motivated, mainly, by two factors: replacement for a modern refrigerator that better satisfies the consumer (although the older equipment is functional and operates effectively), and end of life, whether caused by irreparable premature failures or natural degradation, due to operation time. The sum of these factors leads to these data showed in Fig. 2. It is important to consider that these amount vary each year, especially those related to the first factor (consumer), once, as discussed, this is influenced by the country's economic scenario.

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As discussed, the operation time function discarded equipment distribution data, related to the first quota, was provided by Brazilian environmental Ministry. However, data related to the second factor is not available in literature. So, Junior (2005), proposed a mathematical model that estimate the equipment quantitative with irreparable failures and that were replaced.

Figure 2 shows the refrigerators amount withdrawn for the market in 2011, due to its operation time, distinguishing the two discussed factors. This data is calculated using Junior's (2005). It is important to notice that only 2011 data is showed, and that data for previous years can be obtained from Giuliani (2013).

In first two years there are no records for equipment replacements motivated by technological improvement (BRAZIL, 2012). In Figure 2, one can conclude that the 10 to 14 operation time is the range which most equipment are replaced. As discussed, the next decade's tendency is an early equipment discard.

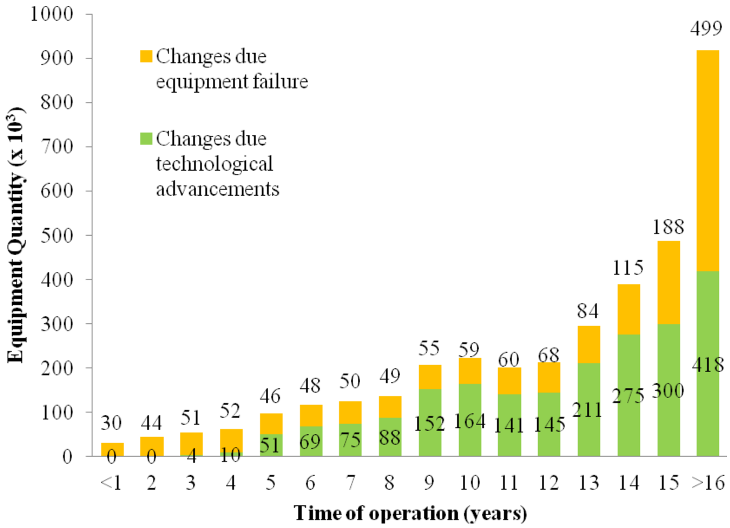

Figure 2 – Quantity of equipment that left the market, in 2011, in function to its operation time.

The economic stability changed the time usage distribution of equipment in Brazilian market. Data provided by Brazil (2012), with Pereira's (2010), and Junior's (2005), Fig. 1, estimative, permit evaluating the Brazilian's market evolution. Fig 2 shows, for each age range, the percentage of operating equipment for the years 2000, 2012 and 2040. It is verified that, actually, the market is getting newer, with equipment in a range of 0 to 10 years, while, in past decades, over 10 years operation time refrigerators represented more than 50% of the market. The future scenario prospects, calculated by the equipment age range percentage evolution, inferring that the market shall consist, predominantly, by refrigerators up to 10 years of operation, i.e., the market shall be each time younger, if the later economic condition remains.

However, it is important to point that the reality to be verified will depend on Brazilian's economy over time. An eventual crisis may change this scenario and the market shall get older again. Otherwise, the tendency, for 2040, is to have mainly refrigerators in a range of 0 to 7 years.

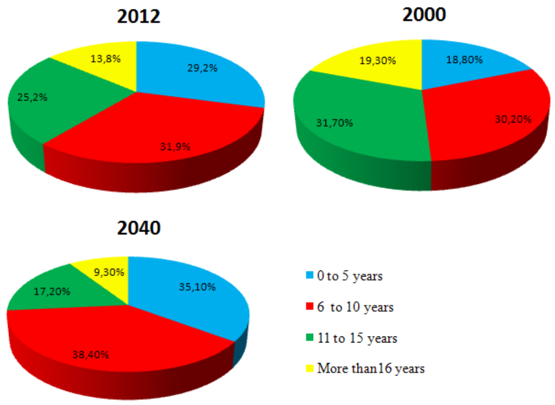

Figure 3 – Refrigerators' market evolution in relation to its operation time function.

Brazilian's refrigerators market is composed by a great variety of models, with distinct characteristics. There are one and two doors refrigerators and lower-capacity ones, such as fridges. The complete characterization, considering the individual properties of each equipment is very difficult due this great variety and lack of data. However, in order to determine the impacts arising from refrigerators use, it is necessary to know, at least, the refrigerant used in the equipment and its electric power consumed.

Since Montreal Protocol signature, the replacement of ozone depletion refrigerants was massive in Brazil. Actually, more than 97% of domestic refrigerators operate with HFC134a. The remaining still uses CFCs and blends. Furthermore, the refrigerant charge used in the equipment is, in average of 0,098kg (PROCEL, 2010). This value was assumed in the present article for the whole refrigerators' market.

The prior knowledge of the equipment's' electric power enables to estimate the amount of electricity consumed and assigns an environmental and financial impact due to its use.

It was found that the average nominal domestic refrigerators' compressors electric power is decreasing over the years due to technological advancements, as shown in Figure 4, for the years between 1991 and 2010 (PROCEL, 2010). It is important to consider this reduction when estimating the impacts, since the difference between the years is over 18%.

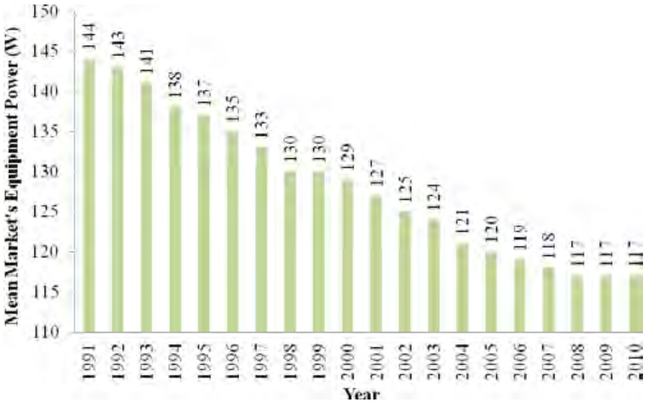

Figure 4 – Brazilian's refrigerators market power evolution over time.

As discussed before, there are no data available in the literature about the amount of equipment that entered and left the market each year organized according the nominal electric power function. Thus, in the present paper, the average values, shown in Fig. 4, are assumed for the whole market. Despite some information quality loss, it is convenient to assume this simplifying assumption, from estimative standpoint, since there are no other sources of data.

3. FIELD EVALUATION OF REFRIGERATORS

A compressor electric power consumption can be divided into two main parts: the one associated to the nominal power consumption during the refrigeration cycle; and the one related to the equipment efficiency loss, that represents an extra power in order to maintain refrigeration effects.

The compressors' nominal power is determined by manufacturers design in standard conditions. The evaluation of refrigerator efficiency is not simple, since several external factors influence in equipment wear, such as the refrigerator's positioning in the ambience; the frequency of door opening during the day; the foods' distribution inside the refrigerator, affecting the inside air flow displacement; among others, and influence the five main physical phenomena that affects its life cycle: liquid slugging; refrigerant flood back; and flooded starts. This leads to valve gaps, clogging e and oil viscosity changing, that results in power consumption increase.

In order to evaluate the loss efficiency of domestic refrigerators' compressors over time, 93 operational equipment, with distinct time of use, whose characteristics resemble those as the average verified in market – one door equipment with internal volume from 310 to 440 liters - were select for consumption analyses test. Thus, it was possible to correlate the power increase over time. The equipment was divided in two groups: the first, with 63 unities, from Brasilia's subway system (used in its kitchens and pantries). This group was selected since the equipment was acquired in a unique purchase, containing only 3 different models in it, and due the fact the unities started its operation in different periods. For this group, the equipment is in a range from 12 to 160 months' time of operation. Thereby, similar refrigerators were compared and it was possible to analyze its efficiency loss evolution. The second group was composed by 14 unities in residences in Brasilia, 4 in Porto Alegre, 2 in Santa Cruz do Sul, 5 in Ribeirão Preto and 5 in Recife. These cities are located in distinct regions in Brazil, with different climates, that could influence the wear in equipment. In this group, the time of operation vary from 3 to 168 months.

In addition, oil particle analyses from oil samples, from a third group, were performed. This group is formed by 27 discarded compressors, due to failure in the electric motor (not in the compressor), in order to avoid contamination due to other problems. The sample collection was realized, under supervision, by a refrigerators' maintenance company, in the consumer's residence, so the risk of oil contamination was minimized. The time of operation, in the group, vary from 8 to 180 months and the samples were submitted to a specialized company in this type of analysis. This equipment was located in Brasilia.

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The monitoring consisted in measure, second by second during a 24 hours period, the refrigerator electric power consumption. Thus, a digital wattmeter was employed. Furthermore, the environment temperature was monitored in 720 seconds cycles, utilizing a digital thermometer.

Acquired data were organized in several spreadsheets, so it was possible to calculate: the equipment average consumption, during on and off periods with cabinet door opened or closed; the effective operation time during the test; the total equipment consumption; and the relative power increase in relation to its nominal.

A typical obtained result is shown in Figure 5, for a 160 seconds sample and indicates: a) refrigerator door opened with compressor turned off; b) door closed and compressor turned off; c) compressor under operation; d) compressor under operation and a door opening. When analyzed data during a 24 hours period, it is suitable to quantify the above variables. It is important to observe that when the compressor starts its operation, momentarily, occurs a power consumption peak. This value was truncated in Fig. 5, so the graphic visualizing is not impaired. Moreover, the data acquisition methodology and data analyses detailing is presented by Giuliani (2012).

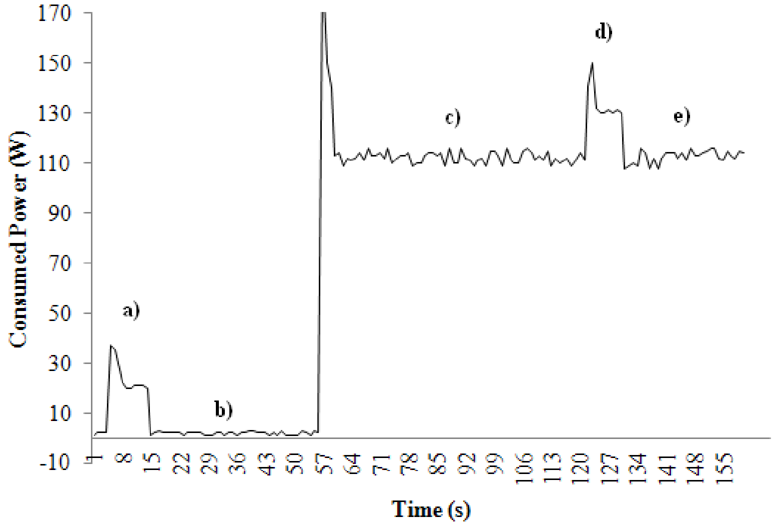

Figure 5 – Typical result for a tested refrigerator.

4. CHARACTERIZATION OF EQUIPMENT DEGRADATION

The acquired data analysis enabled the determination a specific efficiency loss pattern, in time function, for the tested equipment. This section discusses the obtained results and its interpretation.

As exemplified in Fig. 5, the separation of data enabled the determination of average consumption for each compressor during its refrigeration cycle. When compared to its nominal consumption (informed by the manufacturer), it was possible to verify the percentage increase of electric power consumption and associate it to its operation time. The absolute increase may be questioned, since, as discussed, several phenomena interfere the normal operation of a compressor, such as internal temperature, amount of door-openings, air flow inside the equipment, etc. Furthermore, some operating conditions also contribute the wear intensification, such as the distance between the wall and the condenser, complicating the heat transfer. However, the growing of this increase over time has a valid significance.

Thus, in present article, associating the efficiency loss in time function, this means all the degraded factors are being summed, since they were not determined in this study. However, the objective of this paper is to estimate the impact of refrigerators equipment use, taking into account the efficiency loss over time factor, and not to determine the influence of each type of operation mode in the equipment degradation.

The data provided information about temperature variation in ambient and the quantity of door-openings during the test. With respect to the temperature, it was verified that, although the equipment were tested in different regions in the country, with significant temperature variation, the place where the equipment were installed did not presented great temperature amplitude, remaining more established. The correlation between the door-openings and electric power increase was inconclusive, once there is equipment with a higher quantity of door-openings presenting lower energy consumption when compared to other equipment with the same time of usage. This means that other phenomena affects more significantly, in this case.

Thus, considering all degrading factor as a whole, it was possible to determine, for the analyzed equipment, a relation between the percentage increase electric power consumption and its operation time. Data were analyzed separately, considering the two groups and Fig. 6 shows that the difference between them is negligible, when using a polynomial regression of data. Thus, next calculations in this paper consider the whole data set as a unique group.

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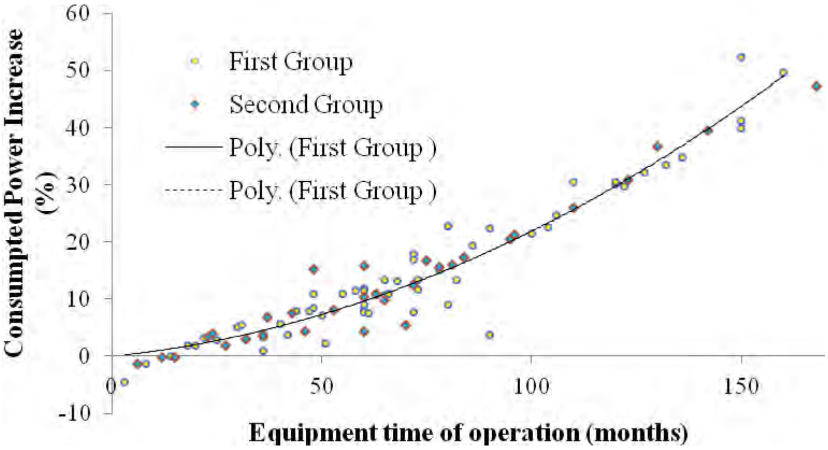

Figure 6 – Consupted power increase acquired data.

Equation (1) represents a polynomial fit from Fig. 6 data, for the estimative of a compressor's energy consumption after t months of operation.

$$P(t) = P_{Nom}\left[1 + \frac{0{,}0012t^2 + 0{,}1159t}{100}\right] \tag{1}$$

where,

P(t)	Electric power, in Watts, consumed by compressor after t months of use;
P_{Nom}	Nominal electric power of analyzed compressor.

4.1 Operation Time Increase

Beyond the energy consumption increase, the compressors effective operational time was characterized. Such as in power analysis, it is important to notice that several external factors, such as ambient temperature, quantity of door-openings, insulating degradation, etc., may affect this data. Thus, only the total operation time was analyzed, independently of the influence of each external factor in its degradation.

Figure 7 shows the effective operational time during a day-period. It is noted that an increasing tendency and equipment shall have operational time increased over 150% in its life cycle.

Equation (2) represents the second order polynomial regression for the acquired data, indicating the operational time during a day, as a function of its time life.

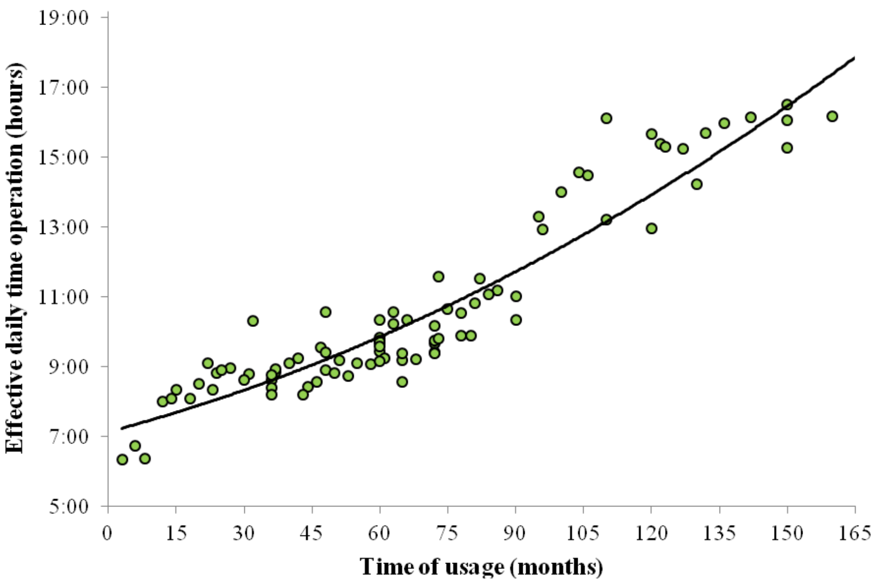

Figure 7 – Operational time in time of usage function.

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$$T(t)=0,0003t^2+0,0221t+6,36 \quad (2)$$

where,

T(t)	Daily time, in hours, the equipment is in full operation;
t	Time, in months, since the equipment started to operate.

4.2 Equipment Daily Consumption as a Function of Its Operation Time

The equipment daily energy consumption is given by the multiplication of its average electric power (verified in data acquisition) and the total time it remained in operation (considered the refrigerators of this paper, it is the product of Eq. (1) by Eq. (2), resulting Eq. (3), that correlates the daily consumption of an equipment to its nominal electric power and its life time operation).

$$P(t)_{24horas} = \frac{P_{nom}}{1000}\left(4,2.10^{-7}t^4 + 5,57.10^{-5}t^3 + 1,1.10^{-2}t^2 + 5,57.10^{-1}t + 6,46\right) \quad (3)$$

where,

$P(t)_{24horas}$	Equipment daily consumption, kWh;
P_{nom}	Nominal electric power of analyzed compressor;
t	Time, in months, since the equipment started to operate.

5. IMPACTS EVALUATION

By means of data analysis both from the literature and from experimental measurements, the financial and environmental impacts of small refrigerators in the Brazilian market can be estimated.

The energy used by residential refrigerators can be estimated on Eq. 3, for the sample considered in this paper. If we assume this equation as valid for the whole small refrigerators' market, it is possible to estimate its annual energy consumption, trough Eq. (4), as:

$$E = \sum_{0}^{t} N_{equip}(t).365.P(t)_{24horas}\text{, t} = 0, 12, 24, 36 \quad (4)$$

where,

$P(t)_{24horas}$	Equipment daily consumption, kWh;
E	Brazilian's market global energy consumption (kWh);
$N_{equip}(t)$	Instant number of refrigerators in a giver year.

Section 2 discussed the amount of equipment in refrigerators' market and the input and output mathematical model used in this market. Based in this information, it is possible to estimate the quantity of refrigerators in the market and its operation time, Nequip(t). Furthermore, section 2 discussed the average electric nominal power evolution over time. If we assume that all equipment in the market can be represented assuming the nominal average power, then global energy consumption by Brazilian market can be calculated.

Table 1 gathers the market's characteristics for 2011. It was not possible to characterize equipment manufactured before 1990 and are still operating, so these are gathered in a unique group, independently of its operational time, whose denomination is "20+".

Table 1 – Main Brazilian's refrigerators market characteristics for 2011.

Operation time (years)	Quantity of equipment (10^6)	Nominal Electricity Power (W)	Estimated Electricity Power (W)	Energy Consumed in 2011 (TWh)
20+	0,98	144	294	1,4
20	1,02	143	280	1,4
19	1,42	141	264	1,9
18	1,52	138	248	2

17	1,92	137	236	2,5
16	2,05	135	223	2,7
15	2,37	133	211	3
14	3,68	130	198	4,2
13	3,65	130	190	3,7
12	3,59	128	180	3,3
11	2,96	126	170	2,5
10	2,85	124	161	2,2
9	3,54	123	154	2,1
8	3,52	120	145	2
7	3,81	118	138	1,8
6	3,93	117	133	1,2
5	2,76	117	129	1,2
4	3,15	117	125	1,7
3	4,72	117	122	1,8
2	5,16	117	120	1,8
1	6,01	117	117	2,1
			TOTAL	**47,2**

Electricity generation cause environmental impacts, especially through carbon dioxide emissions into atmosphere. In Brazil, considering the several sources of energy, it is estimated in about 0,075kg the amount of equivalent CO2 released for each kWh generated (IPCC, 2011). Thus, it is possible to estimative the amount of this gas released by refrigerator appliances. Furthermore, this equipment use refrigerant fluids, also harmful to environment, if emitted into atmosphere, and its impact is evaluated through GWP (global warming potential) index.

Leakages occur in about 2%, per year, of confined refrigerant mass, in domestic refrigerators equipment (IPCC, 2007). As discussed in chapter 2, 97% of refrigerators operate, nowadays, with, averagely, 0,098kg of HFC134a. Assumed all equipment has these characteristics, the direct gas emission impacts can be evaluated. This hypothesis does not interfere, in average terms, the impacts evaluation, since almost all equipment operate with this fluid. Furthermore, the indirect impacts are more intense than the direct ones.

Summing the direct and indirect parcels, in 2011, the Brazilian's refrigerators market emitted 3,64 million tons of equivalent CO2. This value represents the emission of 1,2 million vehicles traveling 50km per day during a year (IBRAM, 2012).

Table 2 gather information about the amount of energy consumed and equivalent CO_2 release in atmosphere in function of equipment time of use. Furthermore, this data is compared when assumed there is no efficiency loss over time. For example, equipment that began to operate in 1996 and worked for 15 years, shall have consumed more than 10.000 kWh in this period, releasing, in atmosphere, 887kg of equivalent dioxide carbon, considering the degradation effects. If there were no wears, the consumption should be about 4.800kWh, with emissions of 354kg of equivalent CO_2. The quantity of equipment with over 15 operating years is estimated in over 11 million unities and they were responsible for more than 1,1 million tons dioxide carbon emitted into the atmosphere.

Table 2 – Impacts due refrigeration appliances in Brazil, in 2011.

Operation time (years)	**Total energy consumed by an equipment through its life-time (kWh)**	**Equivalent CO2 released by one equipment through its life-time (kg)**	**Total energy consumed by an equipment through its life-time without its degradation (kWh)**	**Equivalent CO2 released by one equipment through its life-time without its degradation (kg)**
21+	18849	1414	6532	490
20	17083	1281	6396	480

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19	15598	1170	6048	454
18	14031	1052	5664	425
17	13625	1022	5210	391
16	12228	917	4884	366
15	10685	801	4493	337
14	9129	685	4082	306
13	8984	674	3750	281
12	7870	590	3482	261
11	6803	510	3188	239
10	5905	443	2922	219
9	5073	380	2657	199
8	4172	313	2333	175
7	3517	264	2091	157
6	2886	216	1814	136
5	2356	177	1555	117
4	1853	139	1274	96
3	1437	108	1020	76
2	1056	79	765	57
1	697	52	510	38
0	345	26	345	26

6. CONCLUSIONS AND FUTURE PROPOSIONS

The present paper discussed the efficiency loss in compressors used in domestic refrigerators and the financial and environmental impacts arising for these losses. It was concluded that the consumption and gas emission increase, averagely, about 34% along 15 equipment operation years.

The mean compressors' wear follows a characteristic trend never discussed in literature, as shown in Fig. 5. So far, there were simplified estimative from information obtained from manufactures and whose degradation along 160 months reaches 50%, with a linear relation between degradation and operational time.

Other important verification is about the daily effective operational time. With use, the natural degradation of the whole system oblige the compressor operate for an additional time so the original refrigeration effect is observed. Thus, it was verified that degradations effects are potentiated over time, as shown in Fig. 6, where new equipment operates for about 6 hours a day, while older ones operates for more than 16 hours daily. This causes a vicious circle so much more it degraded, more time it operates, implicating in more degradation.

Furthermore, the indirect gas emission are elevated and necessitate attention, motivating governmental policies for the market renewal, although the companies are getting adapted to international standards and, hence, the equipment efficiency is increasing over the years. In 1990, the mean power of a compressor was 144W and, in 2010, it was reduced to 117W, i.e., 18,75% less.

As sequence of this research, we suggest the data validation in a major number of tested equipment. Furthermore, it is suggested a better evaluation of environmental influence in compressors' degradation, such as temperature, quantity of door-openings, amount of food stored inside the refrigerators, using accelerated life tests in experimental bench. Finally, we suggest a model for evaluation of future scenarios about the financial impacts and environmental degradation in the country in relation to the growth of the amount of refrigeration equipment in the market.

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