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Latin America

Technical improvement of residential refrigerator in Brazil: energy efficiency analysis

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Foreword

The **Energy Discussion Paper** series is intended to disseminate pre-prints and research reports organized or authored by members of the **International Energy Initiative** (Latin American Office) and its associates with the purpose to stimulate the debate on current energy topics and sustainable development.

Any comments or suggestions are welcome and should be addressed to the authors for consideration.

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Apresentação

A série **Energy Discussion Paper** tem o objetivo de disseminar os artigos e relatórios preparados pelos membros ou associados do escritório regional da **International Energy Initiative**. A intenção é estimular o debate sobre temas correntes na área de energia e desenvolvimento sustentável.

Comentários e sugestões são bem-vindos e devem ser encaminhados diretamente aos autores, para consideração e eventuais revisões.

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1. Refrigerator 2. Energy Efficiency

TECHNICAL IMPROVEMENT OF RESIDENTIAL REFRIGERATOR IN BRAZIL: ENERGY EFFICIENCY ANALYSIS

Abstract

Recent technological results in the field of refrigeration systems, embedded electronics, and new materials in general have been incorporated in modern household goods. The use of these technological improvements increases consumer's comfort and create opportunities for manufacturers in the retail market. Nevertheless, the it is possible to speed up technological innovation and contribute to reduce electricity consumption and environmental impacts associated with electricity production. In this context, energy efficiency labels and standards for household appliances have been more widely adopted.

In Brazil until recently the energy consumption labels were used on a voluntary basis. However, the Brazilian government has introduced compulsory legislation to introduce minimum efficiency standards, which should be mandatory in the next years.

The main objective of this study is to provide technical background to support the establishment of energy efficiency standards for refrigerators. The technical improvements suggested in the present study were evaluated in an experimental setup available in a specialized refrigeration laboratory.

Also the study considers the additional manufacturer costs for producing more efficient refrigerators, the cost for the end-user and the reduced environmental impacts due to the lower demand by power plants based on burning natural gas. The present analysis is based on Life-Cycle Cost Analysis (LCCA) methodology that consists of applying statistical and economic engineering approaches to analyze environmental and economic overall impacts. Initially tests were performed to get basic information about a refrigerator with 330-liter of adjusted volume[1], a popular model found in the Brazilian market. Technical variables related to the refrigeration system were monitored and recorded. As a result, the dataset obtained could be confronted with results obtained from the simulation of the refrigerator's mathematical model.

Subsequently, the energy performance of the refrigeration system was analyzed in the laboratory according to some other innovations, namely the use of a more energy efficient compressor, a better suction line insulation and partially moving the condenser away of the refrigerator rear.

1. Life Cycle-Cost Analysis Methodology (LCCA)

The environmental degradation is one of the concerns of industrialized and developing countries alike. Therefore, technical innovations for decreasing energy consumption in household appliances help to reduce the impacts of greater electricity generation and also

[1] Adjusted volume = Refrigerator Volume + 1.42 *Congelador* Volume. *Congelador* is a small freezer compartment placed inside the refrigerator and present in Brazilian one-door models.

contribute to decrease customers´ energy bill. One way to look for technical opportunities to reduce appliance energy consumption is through the LCCA/payback analysis. This analysis allows the estimation of the consumer payback period for acquisition of more energy efficient and more expensive device taking into account the device lifetime and its environmental impact. The LCCA methodology, proposed in CLASP (2001) manual, chapter 6 – "Analyzing and Setting Standards", has been considered here for evaluating some possible technical innovations with regards to their impacts in the economy and environment [1].

As an example, some results related to improving energy efficiency in a Brazilian refrigerator obtained using LCCA methodology are presented in Figure 1. These data were in part taken from the reference [2]. In this analysis, the second most sold refrigerator is the 320-L capacity one. Figure 1 also shows retail price and manufacturer cost increasing due to the technical innovations. The cases A and B[2] represent different participation of the efficient model in the retail market (see ref. 2). The technical innovations considered in Fig. 1 are described in appendix 1.

Evidently, the appliance energy consumption (kWh/year) decreases as long as more innovations are incorporated in the refrigerator. On the other hand, the retail price and manufacturer cost increase as well so that some cost limit is realized. In such a case, the LCCA is important since it suggests the trade-off between maximum efficiency and cost increasing. The upper curve in Figure 1 shows that the minimum energy performance standard (MEPS) is established for innovation C3 in case A. The MEPS index is related to the lowest cost to consumers and, in this example, points to a payback period of 7 years.

The LCCA methodology is also useful to estimate the environmental impact, as shown in Table 1 through the CO_2 conservation accounted for the resulting reduced emission in thermoelectric plant. Table 1 summarizes the results from technical innovations in popular Brazilian refrigerators [2].

Table 1. Results summary[3]

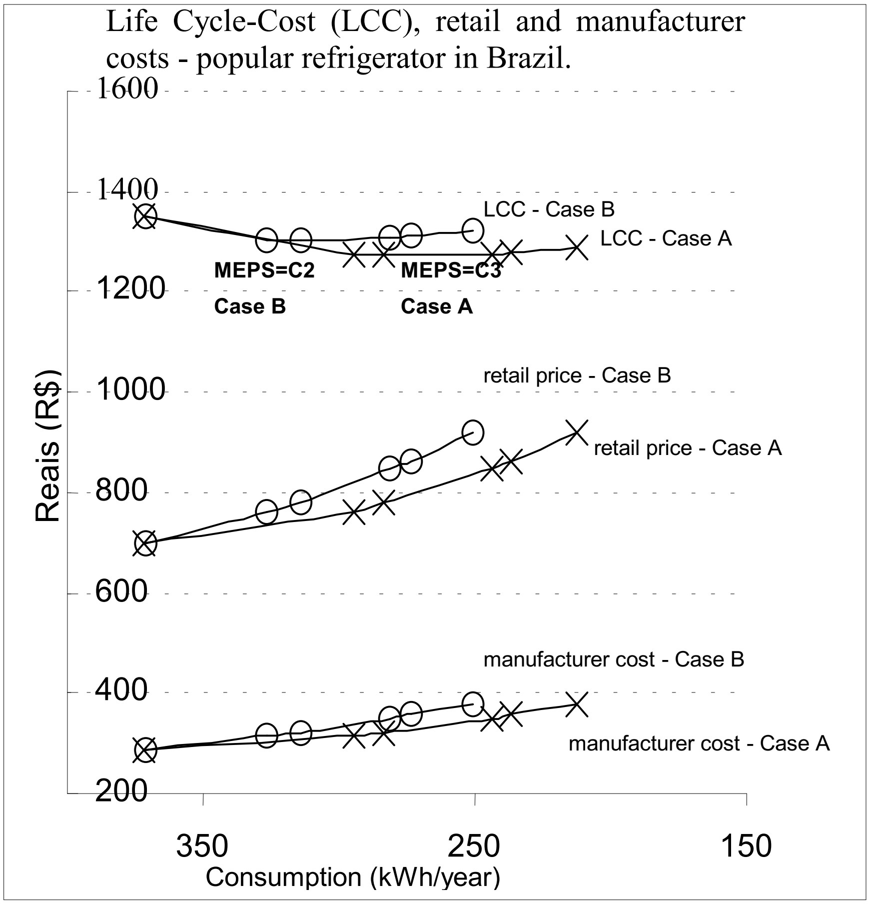
Indicators	Case A
Mandatory Standards (energy reduction)	43% (year 2005) (*)
Payback Period	***7 years***
Improvements	Voluntary Procel label A like a mandatory standard, ***new compressor, increase of the door and walls insulating thermal thickness - ½".***
Energy saved (TWh)	***12 (until year 2010)*** 80 (until year 2020)
CO_2 Conservation (Gg)	***38,160***
Billion R$ saved on the electricity bill	***12***

Notes: It was assumed a coefficient 0.48 kg CO2/kWh (emission from Natural gas fuelled thermoelectric plant). All values were calculated in R$ (2000). (*) compared to the 2000 refrigerator model.

[2] Case A scenario assumes that all refrigerators sold in the country are same as the refrigerator model with 29% of selling in the current market. Case B scenario assumes that technical improvements are applicable only to 47% of the commercialized refrigerators; since the others 53% of the market share is filled by a model that is currently the leader and already is quite technologically advanced.

[3] Table partially reproduced from reference [2].

Fig. 1. Life-Cycle Cost Analysis for popular refrigerators [2] [4]



The main results concerned with this discussion are highlighted using boldface and italic fonts. The technical innovations considered in this example are the use of a more efficient compressor and the increase by ½" (1.27cm) of the door and wall insulating thermal thickness. Certainly, these results foment the technical innovations to be adopted as evidenced by the 12TWh of saved electrical energy and the reduced CO_2 emission of 38 Gg.

2. Characterizing the base -case refrigerator

For this study the base-case refrigerator is a one-door model available in the retail market, receiving the one star classification[5]. This model presents the low-temperature compartment located inside the cabinet and it is denominated *congelador*. In fact, the

[4] The profitable results got from the LCCA method were the main motivation for performing the technical experiment disclosed in this work.
[5] Refrigerators are classified according to Technical Standard ISO7371 [3] as 1, 2 or 3 star refrigerator according to the temperature inside the refrigerator cabinet and in the low-temperature compartment. Models with lower temperatures receive greater number of stars.

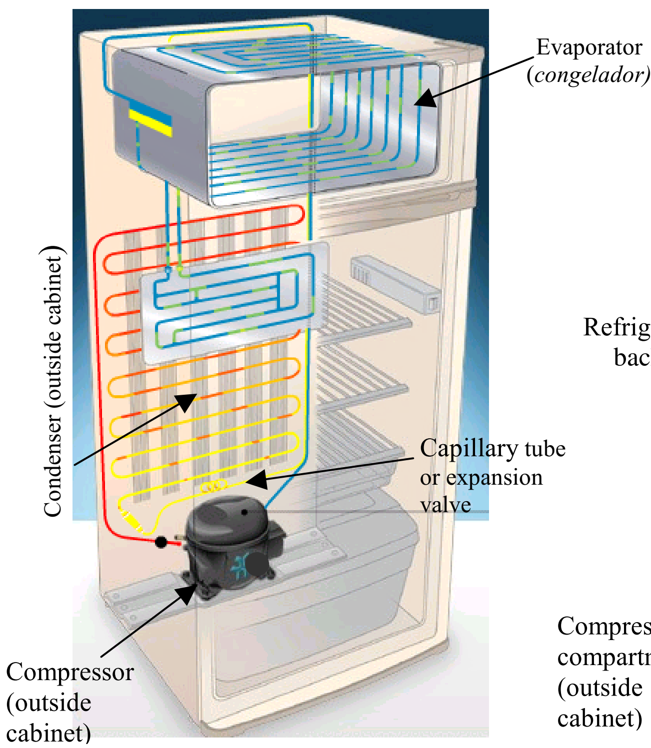
congelador is roughly referenced to a technical part of the refrigeration system called evaporator.

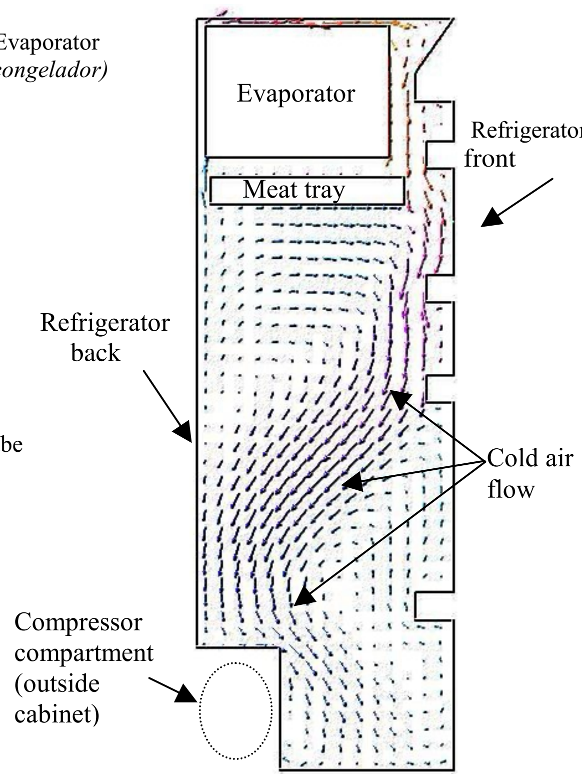
2.1 Refrigerator basic operation

Figure 2 shows the elements of a refrigeration system of a one-door refrigerator commercially available in the Brazilian market. The system is made up of five main elements: electric (motor-) compressor, evaporator, heat exchanger, capillary tube or expansion valve and condenser.

Fig. 2. One-door Brazilian refrigerator airflow model: refrigeration system cabinet (Courtesy of Embra co Inc.)

Fig. 3. Popular refrigerator: natural inside a popular refrigerator





The refrigeration system main component is the compressor, which is supplied by an electrical energy source, and makes the refrigerant fluid (R134a) to flow along the whole refrigeration circuit. Basically the heat absorbed by the evaporator from air inside the refrigerator is released to the environment by the condenser.

Each of the main refrigerator components has the following functions in the refrigeration cycle:

1. The compressor receives the fluid in the gaseous state and pumps it into the condenser. It goes through the compressor and the gas temperature is highly increased as well its pressure.
2. The condenser (located at the cabinet rear) in contact with the external air releases both the heat absorbed by the evaporator and the compressor power, which cools down the refrigerant fluid in the gaseous phase and then liquefies it.
3. After that, the liquid fluid flows through the expansion valve or capillary tube, which is responsible with the compressor for the mass flow. The lower the pressure loss in the expansion device the lower the evaporation temperature and the lower the mass flow.
4. Finally, the cold liquid fluid (with some flash gas) reaches the evaporator where it comes back to the gaseous state by absorbing heat from the refrigerated fluid (internal air).

Mechanically, high-pressure condition exists in the condenser as it is connected to the output of the compressor and a low-pressure is detected in the evaporator connected to the expansion device output.

The peculiarity of this kind of refrigerator is outlined by its internal cooling process. As described earlier, the *congelador* (evaporator) produces cold air, which flows naturally down, while warmer air flows up due to buoyancy forces. Nevertheless, there is no additional element to provide a homogeneous temperature distribution. It implies that the homogeneous cooling capacity depends on the internal air convection heat transfer, which is strongly related to the internal airflow velocity fields. Consequently, the evaporator surface temperature is the controlled variable, which is kept within a determined range.

Usually, more sophisticated models include a mechanical fan for circulating internal air. Figure 3 illustrates a 2-D section for visualizing the internal airflow velocity field in a popular refrigerator obtained by using the CFX-5 commercial package (*Computational Fluid Dynamics Software*). It allows determining the temperature gradient at several points inside the cabinet too. In the Figure-3 refrigerator, there is a main flow of cold air as showed in Figure 3. In such case, the gradient temperature is not uniform, as can be seen below the meat tray and at the bottom, where usually there is vegetable compartment.

2.2 Refrigerator temperature control

The compressor is periodically turned on and off in order to keep the refrigerator temperature within a determined range. Commands for compressor control are delivered by a thermostat (a temperature sensor type) that is disposed over the evaporator guaranteeing its internal low temperature. Technically, it is called ON-OFF control since popular refrigeration systems are completely turned off when a minimum temperature limit is reached.

2.3 Technical characteristics of the base-case refrigerator

Representative results for Brazilian market are expected since the tests are done in the most sold device in the Brazilian market. The base-case fills the standard capacity of 320 liters, which is a reference value for manufacturing, and has 31 liters of free volume within the *congelador* (evaporator). The 6°C negative temperature is sensed inside the evaporator and a maximum of 5°C positive temperature is allowed in the cabinet space according to the technical standards for 1-star refrigerators. Some physical dimensions of the case-base are 1528 mm height, 619 mm width and 691 mm depth. A hermetic compressor is used which has a cooling capacity of 425 Btu/h (125W), displacement of 4.23 cc/rev and energy efficiency rate (EER) of 1,07 kcal/Wh, assembled for low-back pressure (LBP) applications. The electrical specification comprises an operating voltage range of 90-140V supplied by a single-phase 60Hz grid.

3. Laboratory Facility

The technical standard for measuring the refrigerator efficiency requires controlled conditions. Therefore, the Thermal System Laboratory (LST – www.pucpr.br/LST) was chosen since it met the technical standard requirements. Relevant characteristics and apparatus available in LST makes use of a 30.000-Btu/h (8,78kW) test chamber and a complementary set of equipment that allows simulating and monitoring an artificial environment with controlled conditions of relative humidity and temperature. This infrastructure also allows evaluating the thermal-energetic performance of thermal systems such as refrigerators, freezers, compressors and heat-exchangers. The test chamber makes possible the control of temperature and air relative humidity in accordance with the ISO technical standards, that is 32° C and 50%, respectively. A data acquisition system named VXI (manufactured by Tektronix) with 130 input channels is used for measuring a wide set of variable such as, temperature, power, humidity, pressure and other physical variables. Additional information on the LST test apparatus was presented by Mendes et al. [4].

4. Technical results for the base -case refrigerator

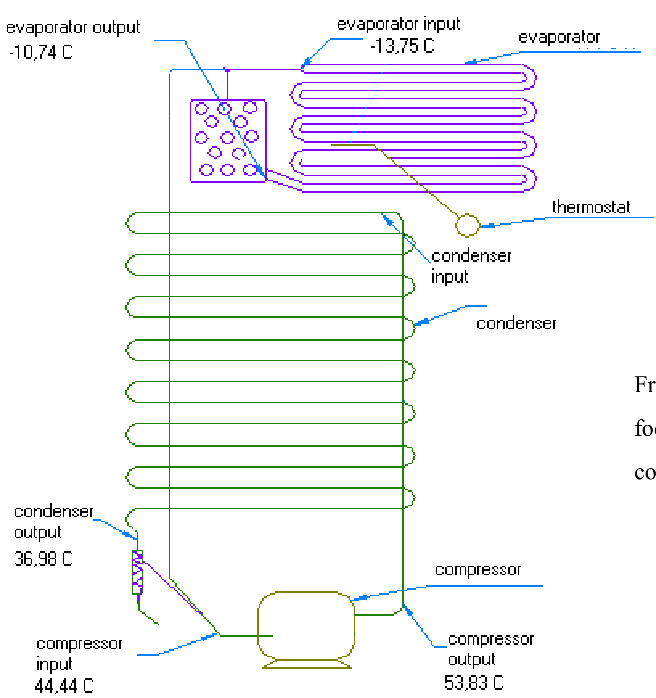
The experimental results performed to characterize the refrigeration system are shown below. The overall refrigeration system is described based on thermal modeling and the temperatures are the variables under evaluation using a computer simulation model. Therefore, the experimental investigation allows sketching a thermal map of the refrigeration system, which may be compared to results obtained from the computer simulation. The instrumentation setup includes the variables measurement in the elements of the systems as appointed in Figure 4. The main points are the temperature at the input and output of compressor, condenser and evaporator.

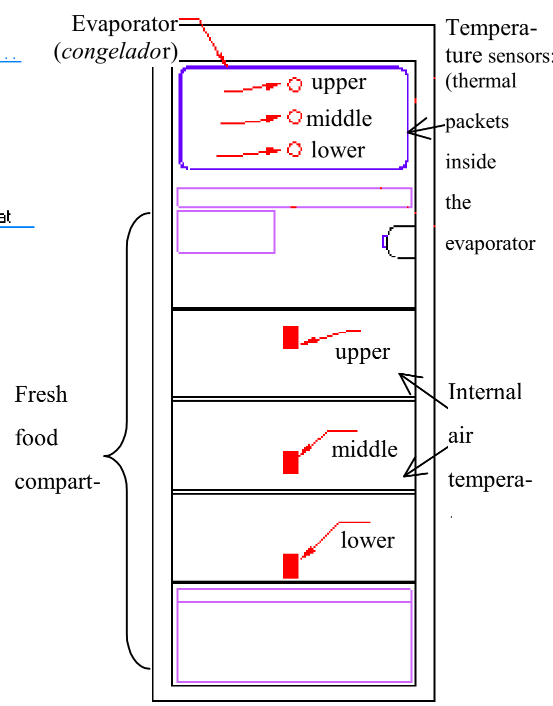
An average value for each measured point is shown in Figure 4. However, since the temperature control is based on ON-OFF strategies all variables are subject to a ripple overlaying the average value. In agreement with the technical standards, the test demands during a period of 24hours registering stabilized temperature at the warmest thermal packaged place within the evaporator and in the refrigerator compartment.

The compressor is on for approximately 9.65 minutes and off for other 14.59 minutes. It implies in a cyclic way of driving as indicated by the ripple showed in temperature waveform. Considering the on and off times period, one can say that the compressor is periodically driven at each 24.24 minutes and the duty cycle is 39.8% (the ratio between the on time and the cycle period, i.e., the running time). As a result, the compressor is turned on 2.47 times per hour.

Fig. 4. Instrumentation setup: thermal variables (measured average temperature is indicated)

Fig. 5. One -door Brazilian refrigerator: instrumentation for electrical -energy consumption experiment





The technical standard also requires setting the air temperature inside the cabinet for registering electrical energy consumption in refrigeration appliances receiving one-star classification. Specifically to the Brazilian one-door refrigerator, the internal temperature at two compartments should be considered, it means, in the evaporator and in the fresh food compartment as shown in Figure 5. In the former, the temperature must be no hotter than -6^{o}C and 5 ^{o}C is the maximum accepted temperature for the fresh food compartment. The evaporator compartment temperature is measured in three distinct thermal packages[6] orderly arranged within evaporator. The packages represent thermal loads and they are manufactured using substances with peculiar thermal properties. Regarding the fresh food compartment, no package is used so that the air temperature is directly measured.

5. Technological improvements for reducing energy consumption

Technical improvements may be done in the overall refrigerator to reduce its electrical energy consumption. Whereas some changes may be readily done in a laboratory other should be time demanding since isolated parts of the refrigerator could be completely redesigned and replaced. In this context, it is assured the use of special software for refrigeration systems called **ERA** (***E****.P.A.* ***R****efrigeration* ***A****nalysis*), distributed by the Environmental Protection Agency – USA. The software validation was based on the results obtained from the base-case characterization.

5.1 Base-case simulation

Very detailed data are necessary for simulating any refrigeration process. In the case of the refrigerator, the data are related to the overall cabinet dimensions and to the main elements composing the refrigeration system such as, evaporator, condenser and compressor. *Electricity consumption results*: The simulated energy consumption was 28.14kWh/month. It is close to the 28.1kWh/month labeled by manufacturer and **28.35**kWh/month recorded in the experimental setup. In consequence of these accurate results, the ERA software was used to simulate other technological improvements related to energy consumption. Software tools are interesting since the effects of technical changes may be quickly verified and present low costs compared to experimental procedures. On the other hand, since ERA does not allow the simulation of other technical improvements that are relevant to the Brazilian base-case model. Therefore, both practical and simulated results are presented, according to the feasibility. Aiming to reduce the electrical consumption three technical changes were done in the refrigerator.

5.2 Innovation A: Suction line insulation

The duct connecting the evaporator and the compressor is called suction line. In such a duct, the refrigerant fluid absorbs heat, which increases its specific volume. At this point, it is important to mention that the higher the specific volume the higher the compressor power for the same inlet and outlet thermodynamics states. This innovation consists of insulating the suction line by using a thermal case to reduce the heat absorbed from the external air. *Consumption result:* The registered consumption was **27.71**kWh/month, which means a reduction of **2.25%** in relation to the experimental base-case consumption. This innovation fits in the ERA software so that the simulated consumption was 27.57kWh/month. The experimental results are preferentially adopted.

[6] Packages are properly manufactured using specific thermal material. The packages provide some inertia to the temperature changing inside the cabinet [3].

5.3 Innovation B: Suction line insulation and condenser partially moved away

The effect of this innovation is cumulative over the first one. Primarily, it is interesting to remind that the condenser works taking heat out of the refrigeration system by natural air convection. Therefore, it is imperative that condenser temperature should be higher than the room air, which is true since the compressor increases the fluid temperature and delivers it up to the condenser. This innovation consists of improving the condenser cooling through moving away the condenser upper part from the refrigerator rear by 10cm. *Consumption result:* A reduction of **6.17%** was observed, compared to the experimental base-case consumption, for a corresponding electrical energy demand of **26.60** kWh/month to experimental tests and 27.21kWh/month to ERA. It means a 3.92% reduction due to only the condenser itself.

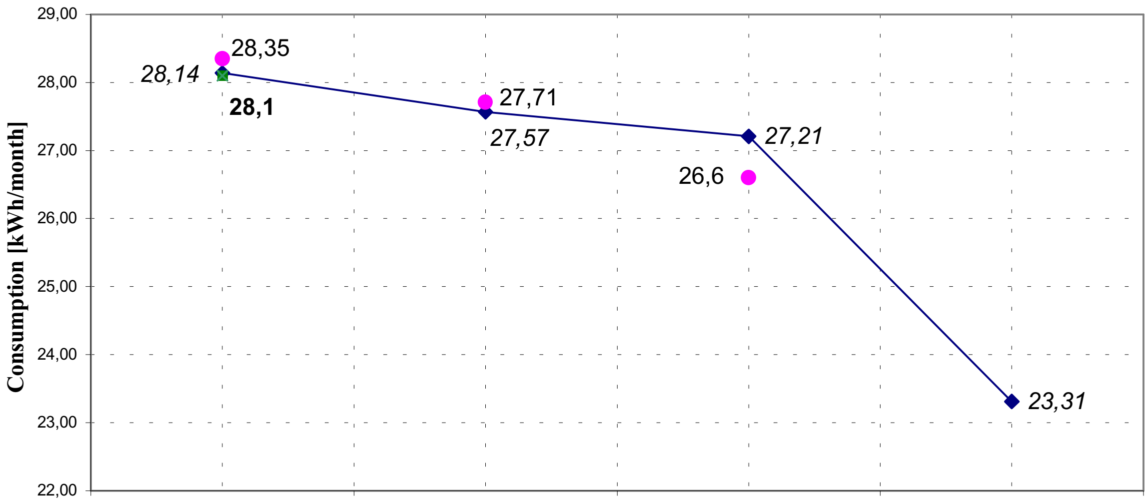
5.4 Innovation B: Suction line insulation, condenser partially moved away and more efficient compressor

This innovation adds more efficient compressor in a cumulative way to the two innovations aforementioned. Compressor efficiency may be found in the compressor datasheet, supplied by the manufacturer, through the EER (Energy Efficiency Rate) acronym. The original compressor found in the base-case refrigerator has EER=4.25 Btu/Wh, whereas the more efficient has EER=5.09 Btu/Wh, representing an efficiency increasing by 19.76%. Therefore, it is a reasonable inference that the refrigeration system efficiency would be considerably increased to the more efficient compressor. *Consumption result:* The overall refrigeration-system efficiency was increased of **17.77**%, which means an energy consumption of 23.31kWh/month from ERA. The experiment is still being performed so the efficiency increasing of 17.77% considers that the experimental results will within the ERA one. These results are related to the ON-OFF control strategy. Nevertheless, new developments involving compressor driving indicates to a new strategy in which the speed controlling is done according to the thermal load variation inside the cabinet. Such a strategy allows a higher efficiency and avoids the cyclical turning on and off process. It is worth to mention that the ON-OFF control declines the power quality, meaning that the voltage at the outlet is distorted.

6. Conclusions

The reduced consumption due to the applied technical improvements aforementioned is sketched in Figure 6. The base-case consumption of 28.1kWh/month is boldfaced, the experimental values are indicated through circles and the ERA results (in italic) are within the continuous line. The values (percentage) indicate the energy efficiency increasing.

Fig. 6. Technical improvements and energetic efficie ncy increasing (%)



In conclusion, these efficiency values (in %) indicate possibilities of developing appliances that are even more efficient. However, it is necessary to examine the added cost to the manufacturing process and for the end-user as well.

The overall cost associated to each innovation may be evaluated using the Life-Cycle Cost Analysis (LCCA) methodology as previously mentioned in section 1. For the technical improvements summarized in Figure 6 the LCCA was not performed on time of writing this article, since any piece of information about cost requires the assistance from local manufacturers. On applying LCCA some basic data about manufacturing costs are necessary such as the cost for changing the factory setup up in order to produce more energy efficiency refrigerators and the markup factor. The latter is defined as the rate between consumer cost and manufacturer cost of refrigerators. For a while, it is worth to mention that no government policy is handled in Brazil to require manufacturers to make public these economic data. Other necessary data are operating costs (as electricity tariff), real discount rate (consumers), life time (in years) and operating expenses.

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8. Appendix 1. Technical improvements for Brazilian refrigerators

Table 2. Efficiency, consumption, standard and cost of the technological innovatio ns

Description of thecnical innovation		%Energy saving (case A)	Cost (R$)
Base-case (C0)	Existing voluntary Procel label A set as a Mandatory Efficiency Standard	4.0 %	0
Innovation 1 (C1)	Base-case + more efficient compressor	20.7 %	60
Innovation 2 (C2)	Innovation 1 + increase of the door insulating thermal thickness - 1,27cm	3.8 %	20
Innovation 3 (C3)	Innovation 2 + increase of the wall insulating thermal thickness - 1,27cm	14.0 %	67
Innovation 4 (C4)	Innovation 3 + increase of the door insulating thermal thickness - 2,54cm	2.8 %	18
Innovation 5 (C5)	Innovation 4 + increase of the wall insulating thermal thickness - 2,54cm	10.0 %	53

Source: innovations costs in dollars using the exchange of 21/august/2002 US$ 1.00 = R$ 3,30 (DOE 1995). Efficiency values were estimated using the simulation software ERA/EPA (Merrian, Verone & Feng) [5].

International Energy Initiative

Latin America

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