

THERMODYNAMIC ASSESSMENT OF HYDROCARBONS APPLICATION IN HOUSEHOLD REFRIGERATOR

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Abstract. *The research efforts and development in the Refrigeration and Air Conditioning sector applied to the use of natural refrigeration fluids is not associated only with the need to preserve the environment alone, but has great importance with regard to the latent need for energy efficient equipment. With this perspective, the present study deals with the thermodynamic evaluation of the use of hydrocarbons refrigerants in household refrigeration systems that utilize HFC134a as a working fluid. A theoretical-computational analysis was developed for R134a, propane (R290) and the selected mixtures (R290/R600a 60%/40%, R290/R600a/R134a 40%/30%/30% and R600a/R290-GLP 70%/30%) in the standard refrigeration cycle ASHRAE, using the thermodynamic and thermophysical properties provided by the REFPROP 6.0 software. The results of computational simulations between the fluids were compared to find the evidence of the best alternative to HFC134a. In this sense, it was observed that the hydrocarbons reduced the levels of pressure on the condenser and evaporator, along with smaller compression tasks necessary in the system, owing to the thermo-physical properties privileged in these fluids. The use of these fluids is also proportionate to lower temperatures of compressor flushing, increasing the life of this highly valuable component of the system.*

Keywords: *natural refrigerants, performance, thermodynamic analysis, drop-in*

1. INTRODUCTION

In September 2007, when it celebrated 20 years of successes of the Montreal Protocol, a new landmark decision was made by all the signatories of that agreement. With the end of the use of CFC's, in 2010, it was decided by the beginning of the replacement of HCFC's already in 2013, ten years in anticipation of the deadline set by the Montreal Protocol for abandoning the use of these gases. Besides the benefits for the recovery of the ozone layer, the object of the Protocol, the measure also brings a huge benefit for climate regime, given the sharp Global Warming Potential (GWP) of HCFC's.

Over its 20 years, the elimination of CFC's that contributed significantly to avoid the issuance of billions of tonnes of CO₂ equivalent and may continue to do so with a cost - benefit of more favorable. In Brazil, the anticipation of the deadline for eliminating CFC's determined by Resolution CONAMA 267/2000 avoided the consumption of 36,500 tonnes of CFC's, which is equivalent, in its effect to global warming, to 360 million tonnes of CO₂. By comparison, national ethanol production, the most successful program of renewable fuels in the world, from 1975 to 2005 avoided the emission of 650 million tonnes of CO₂. Anticipating the time of abandonment of HCFC's will mean further gains.

However, efforts to research and development in the field of Refrigeration and Air - Conditioning apply to the use of natural refrigerants is not only associated with the need to preserve the environment itself, but also has great importance in the latent need for enhanced efficiency energy equipment. Such a feature is observed in Decision XIX / 6 of the Montreal Protocol. In this sense, according to several studies carried out with such fluids, the use of oil operations in the drop -in (replacement process of a refrigerant with no change in the structural components of the refrigerator) in refrigeration provides favorable conditions to reduce consumption energy. Hydrocarbons, such as liquefied petroleum gas (LPG), are environmentally friendly and its products are available in abundance in nature. In this sense, the use of these substances as refrigerants in domestic refrigerators is very attractive. Little information is available in the scientific literature on the use of hydrocarbons in domestic refrigerators. Most work is concentrated on the replacement of CFC-12, and few studies address the replacement of HFC-134a, which is the fluid currently used in such equipment.

Remember that the replacement of HCFC's will be with the introduction of other gases. If the HCFC-22 will be replaced mainly by HFC-134a, an alternative more in consolidated market, much of this gain would be nullified, since the GWP of the two substances is similar.

Refrigerators are among the features that represent the largest holdings in residential electricity consumption in Brazil. This contribution is estimated at around 30 % in 2004 representing an approximate electricity consumption of 23,000 GWh, about 6.3 % of total electricity consumption in the country. Despite progress in increasing efficiency in energy consumption of refrigerators available in the market, which is indicated by the label PROCEL, there are still operating in many Brazilian households with older equipment inefficient technologies.

It is estimated that the participation of refrigerators older than 15 years in the stock in use is approximately 12 %. This suggests extending the use of equipment with the use of inefficient technologies and efficiently degraded. The use

of such equipment may be up to 5 times higher than the new equipment -rated seal PROCEL (Jannuzzi and Melo, 2008).

Thus, we see the importance of searching for alternatives to reduce energy consumption of household refrigerators in Brazil. Specifically in the case of Santa Cruz - RN, the largest share of annual energy consumption occurs in the residential sector, where refrigerators contribute greatly to such a level of consumption, which is 8,695 MWh, for a total of 19,232 MWh including all sectors (industrial, commercial, rural, public authorities, public lighting and other industries) (IBGE, 2007). The realization of this reality site is being examined in the context of developing outreach projects for rural or urban community to lift the energy consumption of refrigeration and study the possibility of working on projects for drop- in equipment. One of the possible alternatives for such a goal is the replacement of refrigerants by other synthetic fluids from a natural products such as hydrocarbons, drop -in operations. Experimental results show reductions in energy consumption, of 4.3% (Mohanraj et al., 2007), 5 % (Wongwises and Chimres, 2005) and up to 20 % (MacLaine-Cross, 1997).

A key element in transforming the market for household refrigerators, specifically for energy efficiency is to develop a process of awareness and strengthening the educational process of the population about the use of these energy-efficient trend. This goal can be achieved by developing a school curriculum that addresses issues relating to energy efficiency and energy use in disciplines of science. Besides development of this curriculum, another important task is to disseminate information to the general public. The media can help raise awareness of consumers and users of refrigeration on the efficient use of energy. Documentaries and public educational programs are other essential components in the campaign for market transformation (Van Buskirk et al., 2007).

Thus, this research project aims to disseminate information about the issue of energy efficiency of cooling applied to the residential sector along with students of IFRN - Santa Cruz, and the development of extension projects in the community as a way of Trairi awareness about the efficient use of energy and issues related to energy policies in the region. Market transformation initiatives for improving energy efficiency in residential applications showed great benefits (Meyers et al., 2003).

This introductory article is part of a research project related to the use of hydrocarbons in residential cooling systems. Is focused on the thermodynamic analysis of the use of these refrigerants as compared to conventional synthetic fluids through the results of computer simulations carried out by using the software REFPROP 6.0 (McLinden et al., 1998), evaluation of thermodynamic and thermophysical properties of refrigerants.

A theoretical analysis was developed for R134a, propane (R290) and selected mixtures (R290/R600a 60 % /40 % R290/R600a/R134a 40%/ 30 % / 30 % and R600a/R290-GLP 70 % / 30 %) in the ASHRAE standard refrigeration cycle (evaporation temperature: -23.3 ° C, condensation temperature: 54.4 ° C, temperature of liquid and suction: 32.2 °C) using the thermodynamic properties of REFPROP 6.0, as recommended by Kim et al. (1998).

2. LITERATURE REVIEW

By demonstrating the relationship between emissions CFC's and destruction of the stratospheric ozone layer made by Rowland and Molina in 1974 and the subsequent signing in 1987, the Montreal Protocol in 1987, which imposed targets for the elimination of HCFC's CFC's, the issue of environmental impact of air conditioning and refrigeration industry seemed so resolved. However, the discussion about global warming, which for some time had been gaining strength in the scientific community, turned out to lead in 1997, the signing of the Kyoto protocol, which took on targets for reducing emissions of greenhouse gases (among they HFC 's) by developed countries. Again, the industrial and scientific community working in the sector of refrigeration and air conditioning world was facing the need to develop a new generation of refrigerants now also committed to preserving the environment.

Richardson and Butterworth (1995) conducted experiments to investigate the performance of hydrocarbons in a refrigeration system for hermetic vapor compression. Tests were performed using R12, propane and mixtures of propane /isobutane composition varying around 50 % / 50 %. The authors found that the mixture of propane / isobutane with composition of 50 wt% of propane has a higher COP, less load on the system and lower the wall temperature of the compressor compared to R12.

MacLaine-Cross (1997) showed that the hydrocarbon refrigerants provide 20 % reduction in energy consumption compared to CFC12 and HFC134a.

Kim et al. (1998) evaluated the performance of hydrocarbon refrigerant R600a as an alternative to R12 in a automatic defrost domestic refrigerator of 215 liters capacity. The authors developed a theoretical analysis using the software REFPROP, cycle-based vapor compression refrigeration ASHRAE standard, and then conducted a series of tests with the R600a. For the tests only the compressor and capillary tube were modified equipment. The tests were conducted under controlled conditions of temperature and relative humidity (30 ° C and 75 % respectively).

Alsaad and Hammad (1998) examined the use of liquefied petroleum gas (LPG) with 24.4 % of R290, R600 of 56.4% and 17.2% of R600a as a refrigerant for drop-in domestic refrigerators with R12. The authors reported an evaporator temperature of -15 ° C and 3.4 coefficient of performance for a condensing temperature of 27 ° C when LPG is used.

Hammad and Alsaad (1999) investigated the performance parameters of household refrigerator unmodified when R290 (100%), R290/R600/R600a (75/19.1/5.9%), R290/R600/R600a (50/38.3/11.7%) or R290/R600/R600a (25/57.5/17.5%) are used as possible replacement alternatives to R12. The authors showed that the mixture of hydrocarbons with R290/R600/R600a (50/38.3/11.7%) is the best alternative refrigerant.

Tashtoush et al. (2002) presented an experimental study on the performance of domestic refrigerators vapor compression with new blends of hydrocarbon / hydrofluorocarbon as refrigerant for replacement of CFC12. The results showed that the mixture of R600, R290 and HFC134a has an excellent performance.

Lee and Su (2002) conducted an experimental study in the use of isobutane in a household refrigerator. The results showed that the coefficient of performance was comparable with that obtained by CFC12 and HCFC22 when used as refrigerants.

Akash and Said (2003) reported that LPG has better performance than the R12. The results showed that a load of 80 g of LPG had the best results when used in the same refrigerator.

Sekhar et al. (2004) investigated the mixture of HFC134a/hydrocarbons in two systems of low temperature (household refrigerator and freezer) and two medium-temperature systems (vending machine and bottle cooler). The authors concluded that a mixture containing 9 % of hydrocarbon mixtures (mass) has the best performance, resulting in 10-30 % and 5-15 % reduction in energy consumption in systems of medium and low temperature, respectively.

Fatouh and El Kafafy (2006a) evaluated theoretically a mixture of hydrocarbons composed of 60% and 40% R290/R600 as a better drop-in replacement for domestic refrigerators based on HFC -134a under abnormal weather conditions, subtropical and tropical regions.

3. THEORETICAL-COMPUTATIONAL MODELING

First we have developed a theoretical-computational analysis of the cooling system proposed in order to obtain estimates of the process of system operation as well as its performance. For this analysis we used dedicated software, namely REFPROP 6.0 (McLinden et al., 1998), for evaluation of thermodynamic and thermophysical properties of refrigerants.

A theoretical analysis was implemented for the use of R134a, propane (R290) and selected mixtures of R290/R600a 60 % / 40 %, R290/R600a/R134a 40 % / 30 % / 30 % and R290/R600a 30 % / 70 % in the ASHRAE standard cycle cooling (evaporation temperature: -23.3 ° C, condensation temperature: 54.4 ° C, temperature of liquid and suction: 32.2°C) using the thermodynamic properties of REFPROP 6.0, as recommended by Kim et al. (1998). The coefficient of performance of systems for commercial and domestic refrigeration is increased from 10 to 20 % when using mixtures of hydrocarbons containing R600a and R290 (Sekhar et al., 2004).

In order to simulate the vapor-compression refrigerator some assumptions are necessary. These are: a) steady state operation, b) no pressure loss occurs in the pipes, that is, pressure changes occur only at the compressor and capillary tube, c) gains or losses of heat are neglected; d) compressor presents ideal volumetric efficiency and ideal isentropic efficiency of 75 % (Fatouh and El Kafafy, 2006a). Figure 1 shows the thermodynamic cycle model used in theoretical and computational analysis.

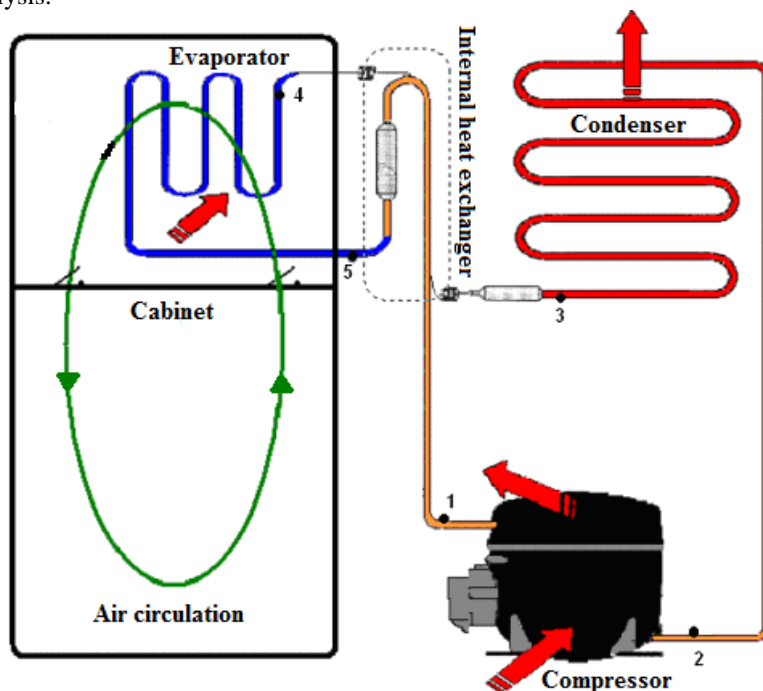


Figure 1 - Real thermodynamic cycle of a household refrigerator. (Borges et al., 2010)

For drop-in acceptance of a working fluid in a refrigeration system that already exists, some important performance characteristics should be considered. These are: operating pressure, volumetric cooling capacity, coefficient of performance and compressor discharge temperature (Fatouh and El Kafafy, 2006a). The refrigerant must have a minimum number of essential characteristics favorable, among which the most significant are: low density in the liquid phase, high latent heat of vaporization, low specific volume in the vapor phase and low specific heat in the liquid phase. These characteristics will be evaluated and compared between the fluids in question, as recommended by Poggi et al. (2008).

The volumetric cooling capacity (Q_{vol}) is a measure of the compressor size for required operating conditions. Expresses the effect of cooling obtained per 1 m³ of refrigerant entering in compressor (Poggi et al., 2008). It should be noted that, as the volumetric capacity of cooling increases, the size of compressor required is reduced. The volumetric cooling capacity (Q_{vol}) can be estimated as follows

$$Q_{vol} = \frac{(h_5 - h_4) \cdot \eta_{vol,ideal}}{v_1} \quad (1)$$

where h_5 and v_1 are respectively the specific enthalpy and specific volume refrigerant saturated vapor condition at the compressor inlet and h_4 is the enthalpy specific to the refrigerant entering in evaporator, according to Fig 1. The pressure ratio (PR) is defined as the ratio between the condensation pressure (P_{cond}) and evaporation pressure (P_{evap}), e.g.

$$PR = \frac{P_{cond}}{P_{evap}} \quad (2)$$

The condensation and evaporation pressures are determined according to the condensation and evaporation temperatures, respectively.

The coefficient of performance (COP) relates the cooling capacity and power required and indicates the overall power consumption for a desired load. High COP means low energy consumption for absorption of the same cooling space to be refrigerated. Can be expressed as

$$COP = \frac{Q_{evap}}{P_{comp}} \quad (3)$$

where Q_{evap} is the cooling capacity and P_{comp} is power required to drive compressor. The energy balance in the evaporator results

$$Q_{evap} = \dot{m}_r \cdot (h_5 - h_4) \quad (4)$$

The power required to drive the compressor can be described as

$$P_{comp} = \dot{m}_r \cdot (h_2 - h_1) \quad (5)$$

The real specific enthalpy of superheated refrigerant vapor leaving to the compressor (h_2) can be calculated as follows

$$h_2 = h_1 + \frac{(h_{2,is} - h_1)}{\eta_{is,comp}} \quad (6)$$

where $\eta_{is,comp}$ is the isentropic efficiency of compressor and $h_{2,is}$ is the specific enthalpy of superheated vapor refrigerant leaving to the compressor for isentropic compression process.

The refrigerant mass flow (\dot{m}_r) can be estimated using the following equation (Tashtoush et al., 2002)

$$\dot{m}_r = \frac{Q_{evap}}{q_{evap}} \quad (7)$$

where Q_{evap} is the cooling capacity in kW and q_{evap} is the specific cooling effect specific in kJ/kg. The mass flow in computer simulation are given in kg/h.

The compressor discharge temperature ($T_2 = T_{DIS}$) is an important parameter, because its effect on the compressor components and the stability of lubricants. This temperature was determined using both data and condensation pressure and real specific enthalpy at the outlet of the compressor, determined by Eq.06.

In the cycle analysis, the same cooling capacity was applied to all simulations of refrigerants considered. The cycle cooling capacity of 143 W was obtained by conversion of freezing capacity (3.5 kg/24h) of a 210 L household refrigerator, provided by the manufacturer.

4. RESULTS AND DISCUSSIONS

Applying the various equations in cooling circuit showed in Fig.1 under predetermined conditions of operation (ASHRAE cycle) and using software REFPROP 6.0 (McLinden et al., 1998) were obtained operating data relating to selected refrigerants. Table 1 shows the results of simulations.

Table 1 – Hydrocarbons characteristics in the standard ASHRAE refrigeration cycle.

Refrigerants Parameters	R134a	R290	R290/R600a (60/40)	R290/R600a (30/70)	R290/R600a/R134a (40/30/30)
Condensation pressure at 54,4°C (kPa)	1470,0	1883,0	1370,5	1050,6	1604,0
Evaporation pressure at -23,3°C (kPa)	114,8	216,6	140,6	99,85	174,7
Pressure difference (kPa)	1355,2	1666,4	1229,9	950,75	1429,3
Pressure ratio	12,8	8,7	9,74	10,52	9,18
Refrigeration effect (kJ/kg)	185,58	354,47	347,85	342,11	279,7
Volumetric cooling capacity (kJ/m ³)	743,719	1171,9	819,718	619,5	980,391
COP	2,049	2,041	2,093	2,160	2,085
Cooling capacity (W)	143	143	143	143	143
Flow mass (kg/h)	2,773	1,452	1,479	1,504	1,840
Discharge temperature (°C)	139,5	134,5	128,8	123,6	126,0
Capillary tube inlet temperature(°C)	32,2	32,2	32,2	32,2	32,2
Suction specific volume (m ³ /kg)	0,2121	0,2571	0,3607	0,4694	0,2425
Liquid phase specific heat (kJ/kgK)	1,44733	2,8002	2,66510	2,57641	2,28916
Liquid phase density (kg/m ³)	1183,27	483,44	505,718	523,598	588,688

Analyzing the results presented in Table 1, the higher weight fraction of propane (R290) provides higher condensing temperatures and less evaporation temperature, which can lead to large ice formation on the evaporator. The mixture of R290/R600a (60/40) has the best solution in this regard.

The mixture of R290/R600a (60/40) has the lowest densities of liquid along with the pure R290, thus providing reduced friction losses in the system. This mixture also has the lowest densities in the vapor and liquid, with an

expected reduction in total work of compression. The density reduction values is more important than an increase in latent heat of vaporization of the fluid (Poggi et al., 2008).

The decrease in the R134a proportion leads to a reduction in power required compression and heat transfer in the condenser. The mixture of hydrocarbons with R134a gives an increase in lubricity and miscibility of lubricating oil with R134a (Tashtoush et al., 2002). The vapor densities under suction conditions for mixtures and R290 to have lower than those of R134a, corresponding to a lower charging of necessary fluid mass in the system relative to R134a.

It may be noted further that the latent heat of vaporization (refrigeration effect) of the R290/R600a is about twice that of R134a. However, due to the reduced specific volume of R134a in suction, the volumetric cooling capacities of the two fluids are quite close. In order to accept a working fluid as a substitute for domestic refrigeration system, a similar volumetric refrigerating capacity and performance compared with existing refrigerant are required (Fatouh and El Kafafy, 2006a).

5. CONCLUSIONS

The research and development efforts in the field of Refrigeration and Air-Conditioning apply to the use of natural refrigerants is not only associated with the need to preserve the environment, but also has great importance because the latent need of increased energy efficiency of equipments.

Hydrocarbons, such as liquefied petroleum gas (LPG), are environmentally friendly and are available in nature, the use of these substances as refrigerants in domestic refrigerators is very attractive.

According to the thermodynamic analysis developed for hydrocarbon fluids may be noted that these lower levels of pressures in the condenser and evaporator.

The use of R290 and mixtures involving hydrocarbons provides a tripling of the latent heat of vaporization compared to R134a. This factor leads to a reduction of about 50 % of the need to mass charge of refrigerant in the cooling system for a same capacity of the equipment.

Hydrocarbons provide lower compressor discharge temperatures, providing longer life to these components. The coefficient of performance of the system with hydrocarbons and mixtures grew by about 5 % compared to R134a. Consequently, lower compression works are required to hydrocarbons compared to R134a due to thermophysical properties.

In order to consolidate the hydrocarbons and their mixtures as substitutes for synthetic fluids, such as HFC134a, the refrigeration industry should focus its efforts on developing compressors suitable for volumetric cooling capacity of natural refrigerants, and the development of new design methodologies of heat exchangers, since the mixtures behave differently from pure fluids with respect to phase change.

6. ACKNOWLEDGEMENTS

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