ALTERNATIVES REFRIGERANTS TO BE USED IN AUTOMOTIVE AIR CONDITIONING SYSTEMS IN REPLACE THE R-134a

Enio Pedone Bandarra Filho, bandarra@mecanica.ufu.br
Oscar Saul Hernandez Mendonza, oscarhm@mecanica.ufu.br
Faculty of Mechanical Engineering – Federal University of Uberlandia, Av. Joao Naves de Avila, 2121 – Uberlandia-MG-Brazil

João Bosco Coelho, bosco-coelho@ig.com.br
Federal Institute of Maranhão, Imperatriz Campus – Imperatriz – MA – Brazil

Abstract. This article shows a review of alternatives refrigerant in automotive air conditioning system. An extensive review was conducted and showed an evolution of the thermal performance of the alternative refrigerants (HFC-152a, HFO-1234yf and carbon dioxide) flowing as a refrigerant in automotive air conditioning system. Experimental results in vehicles are presented, comparing the performance in terms of cooling and fuel consumption. The refrigerant HFO-1234yf has some positives characteristics, the GWP is only 4 and the life time in atmosphere is around 11 days, however, the negative characteristic is associate to the flammability, higher than ammonia and HFC-32 and lower than HFC-152a and propane. The most interesting results showed the cooling time of the interior cabin was, significantly, reduced in all tests performed when the refrigerant used in the system was the carbon dioxide, including results for small power vehicles in comparison with the R-134a baseline.

Keywords*: Automotive, CO2, Carbon Dioxide, HFO-1234yf, Air Conditioning.*

1. INTRODUCTION

The new rules imposed by European Union, where in 2011 will not be allowed new vehicles leaving the assembly with air conditioning system using any refrigerant with GWP (Global Warming Potential) higher than 150, the industry and academy joint in a great effort to develop and evaluate new alternatives, such as chemical refrigerants or natural refrigerants.

Historically in the automotive sector, the refrigerants CFC-12 and HCFC-22 were the work fluid used in air conditioning systems until the beginning of nineties, since the signature of the Montreal Protocol, where they fixed the phase out of CFC-12, in 1996 for developed countries and 2010 for developing countries, such as Brazil. With this, the refrigerant HFC-134a, that is very similar to R-12, basically, dominated the market of the automotive air conditioning systems. However, due the high global warming potential of the R-134a, 1430 in 100 years, the European Union, after 2011, decided not accept the introduction of the automotive air conditioning systems with work fluid with GWP higher than 150 in new models and in 2017, this rules will be extended for all vehicles.

Therefore, the automotive industries work, basically, with three situations:

(1) use of the refrigerant HFC-152a in secondary system, since this refrigerant has GWP of the order of 124;
(2) a new refrigerant developed by the chemical industries, a HFC called HFO-1234yf, GWP of 4;
(3) the natural refrigerant, CO_2 (R-744), that is the reference of GWP, with the value of 1.

Each refrigerant, above mentioned, has its own particularities and they must be taken in account in the final decision of the manufactures, however, up to now, there is not a clear definition on this. Therefore, they are waiting all tests made by many companies and universities to decide the best. A brief introduction on these fluids will be presented as follow:

1.1 HFC-152a

The fluid HFC-152a used as refrigerant in automotive air conditioning systems can be considered a transition, since this fluid is produced commercially. However, the use of this refrigerant needs some special care and must be use in combined cycle, since this refrigerant is flammable. The suggestion is to use two loops, the refrigerant R-152a loop isolated of the automobile's cabin and water or ethylene glycol as secondary fluid inside of the cabin. Some authors found a better performance of the R-152a in comparison with the R-134a.

Kim et al. (2008) conducted an experimental study comparing the R-134a and R-152a in single stage system. The results showed a better performance of the R-152a in relation to the R-134a, for the same compressor velocity, the COP for the R-152a was higher between 30 to 42% and the refrigeration capacity for the R-152a presented values between 20 and 41% higher than obtained for the R-134a.

Ghoudbane and Fernqvist (2003) studied experimentally the refrigerant HFC-152a flowing in a combined cycle of an automotive air conditioning system, where the secondary fluid used was water. The authors used for the comparison a system with 1.3 kg of R-134a and 0.59 kg for the R-152a. The results showed, basically, the same thermal performance and in relation to the fuel consumption, the system with R-152a presented 10% higher fuel consumption in comparison with the system with R-134a and this is related to the weight of the full system, since for the R-152a is heavier.

Concluding, the refrigerant R-152a has been considered as a possible substitute for the R-134a, however the negative point is related to the flammability, since this fluid is highly flammable.

1.2 HFO-1234yf

One great bet of the chemical industries was the development of a new HFC chemical compound, called tetrafluorpropene, or commercially known as HFO-1234yf. This fluid has a value of the global warming potential, GWP, of 4 (100 years) and other interesting characteristic is the short lifetime in atmosphere, of the order of 11 days. However, this new compound is considered flammable and this negative characteristic can interfere in the acceptation by the manufacturers. Other negative consequence is that this fluid in contact with water can create a highly toxic acid, called hydrofluoric.

Most manufacturers are waiting the confirmation of the HFO-1234yf as substitute of the HFC-134a, since, practically, the same components of air conditioning system can be used, avoiding significant modifications in the vehicle design. However, many components and compatibility tests must be developed to avoid future problems. The lower flammability limit (LFL) observed for the HFC-152a is around 3.9% in volume in air and for the HFO-1234yf of 6.5% in volume, in other words the HFO-1234yf is flammable, but less than R-152a, (Minor, 2007).

Table 1 shows a comparison of some properties of the refrigerants R-134a and HFO-1234yf. As can be observed, according to the manufacturer, the properties of the HFO-1234yf are very close of the R-134a, showing, also, a GWP lower, of 4, compared to R-134a with GWP of 1430.

Table 1. Comparison of some properties of the refrigerants HFC-134a and HFO-1234yf.

Property	HFC-134a	HFO-1234yf
Boiling temperature	-26°C	-29°C
Temperature of critical point	102°C	95°C
Saturation pressure (with T=25°C)	665 kPa	677 kPa
Saturation pressure (with T=80°C)	2630 kPa	2440 kPa
Global Warming Potential (100 years) – GWP	1430	4
Ozone Depletion Potential – ODP	0	0
Atmosphere life time	14.5 years	11 days

Figure 1 shows a comparison between the vapor pressure (saturation pressure) of R-134a and HFO-1234yf, for a temperature range varying from -30 to 90°C, Koban (2009).

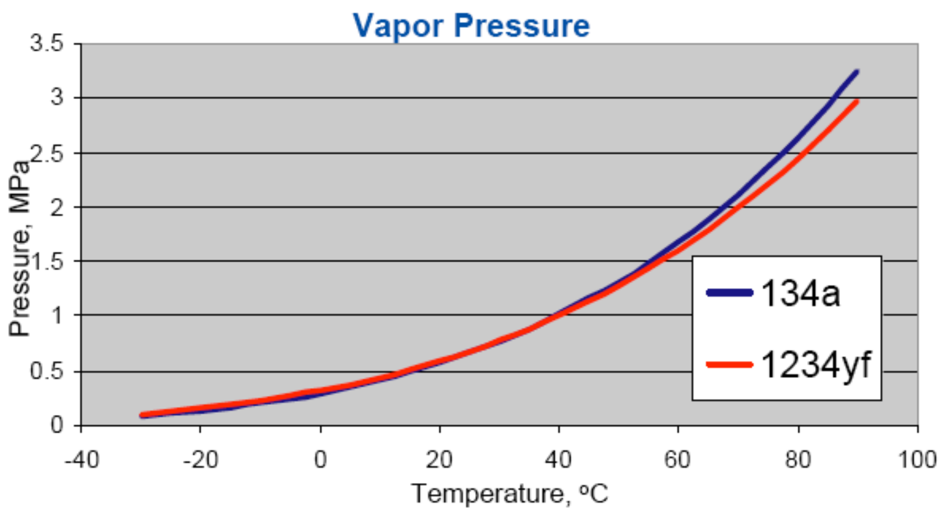

Figure 1. Comparison between the vapor pressure (saturation pressure) of HFC-134a and HFO-1234yf, for temperature range varying from -30 to 90°C, Koban (2009).

1.3 CO_2 – R-744

The use of carbon dioxide (CO_2) in refrigeration systems is not new, since the CO_2 was first proposed as a refrigerant by Alexander Twining as reported by Bodinus (1999) in 1850. Lowe apud Bodinus (1999) conducted experiments with CO_2 in military balloons and also designed an ice machine using CO_2 in 1867. The same author has developed further, a machine to carry frozen meat on ships. As a curious example, the Fig. 2 depicts an advertisement of a company in the beginning of twenty century, commercializing ice machines, using carbon dioxide as a work fluid and focusing the safety system. A quick literature review showed that refrigeration systems, that use CO_2 as refrigerant, have been developed over the years and reached a peak between the years 1920 and 1930. CO_2 was widely used on ships while another natural refrigerant, ammonia (NH3), was more common in refrigeration systems used on land.

With the arrival of halogenated refrigerants, known commercially as "FREON", mainly CFC-12, applications with the CO_2 was suppressed. The main reason for this decline was the loss of capacity and increasing pressure to high temperatures. In these conditions, ammonia continued to gain space over the years, dominating the market for refrigerants in a segment called refrigeration industrial.

Figure 2. Advertisement of a company in the beginning of twenty century, commercializing ice machines with carbon dioxide as a work fluid.

In nineties, discussions about advantages of using CO_2 arise again, due to its ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) characteristics. The reason for this resurgence was mainly the removal and restriction of CFC and HCFC refrigerant and also reducing the inventory of NH_3 (ammonia) in refrigeration systems.

Called natural refrigerants, as CO_2, ammonia and hydrocarbons such as propane and butane were the most used options, but the latter have their disadvantages such as toxicity (ammonia) and flammability (hydrocarbons). In comparison, CO_2 is not toxic, only in large quantities, and is not flammable, but has a dual role in environment. Carbon dioxide is necessary to life on earth, but also collaborates to greenhouse effect.

Nowadays, there are two lines of research well defined on CO_2 applications. The first one focuses on transcritical cycles called, single stage, mainly associated with automotive air conditioning systems. The second focuses on implementation cycles called cascade systems, which is the combination of two simple stage cycles, where CO_2 is the refrigerant of the low temperature circuit (or low pressure), with evaporation temperatures ranging from -50°C to -30°C and between -30 and -10°C of condensation temperature. This paper deals the state-of-the-art review of alternative refrigerants of automotive air conditioning systems.

2. FUNDAMENTALS AND REVIEW

Transcritical cycle is characterized by the fact that there is a process during the cycle, where temperature and pressure conditions go beyond the critical point. An interesting comparison between air conditioning cycles operating with CO_2 and R-134a can be seen in Fig. 3, Brown et al. (2002). In CO_2 case, left side of the figure, the critical temperature is 31.1°C, therefore, the process of Figure 2-4, is characterized by being in the region above of the critical point. In R-134a case, the processes occurring below the critical point, right side of the figure. In this case, the main difference between cycles with R-134a and CO_2 occurs on the line after compression, where in conventional system occurs the change of phase (vapor to liquid), known as fluid condensation, while in transcritical cycle only vapor (supercritical) is cooled, without change of phase.

Brown et al. (2002) conducted a numerical study comparing the coefficient of performance, COP, and air temperature in Gas Cooler or Condenser for different compressor speeds. The results showed that system with R-134a presented the best COP. It is interesting to note, that these tests were conducted in 2002, and possibly had problems in modeling the Gas Cooler and the compressor, because these equipments showed the greatest entropy generation.

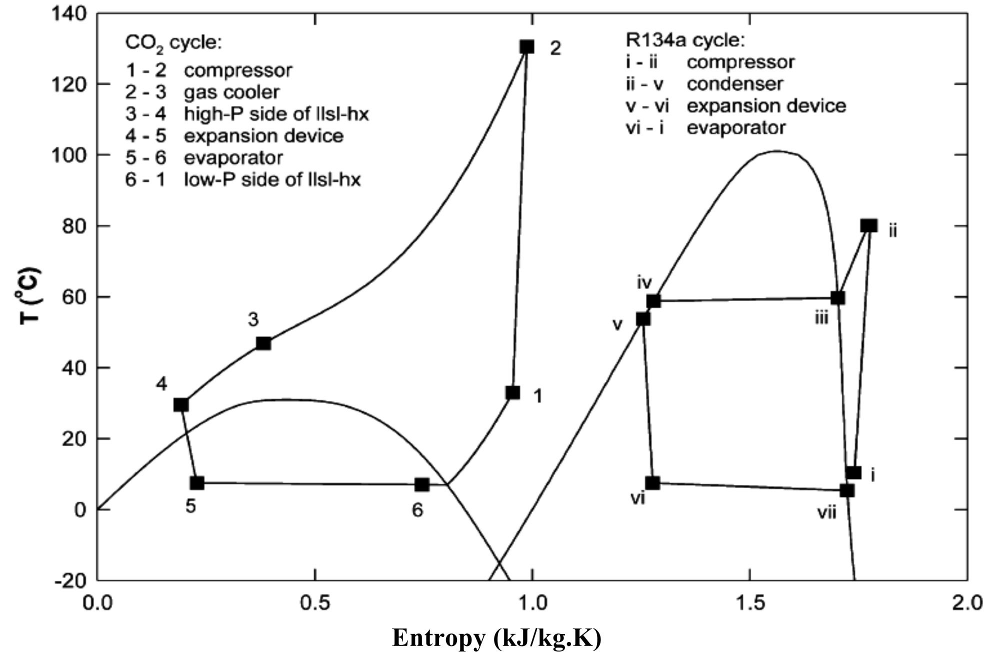

Figure 3. Diagram temperature versus entropy for two automotive air conditioning cycles using CO_2 (left) and HFC-134a (right). Brown et al. (2002).

Figure 4 shows an experimental study made by Liu et al. (2005) comparing the refrigeration capacity, the COP and the inlet air temperature in the Gas Cooler with the variation in the face speed of air in the evaporator. It is interesting to note that the COP decreases with increasing temperature of air in the Gas Cooler for two face speeds tested, 1.4 and 2.5 m/s. Meanwhile, values of the COP for face speed of 2.5 m/s are about 50% higher than those obtained for speed of 1.4 m/s.

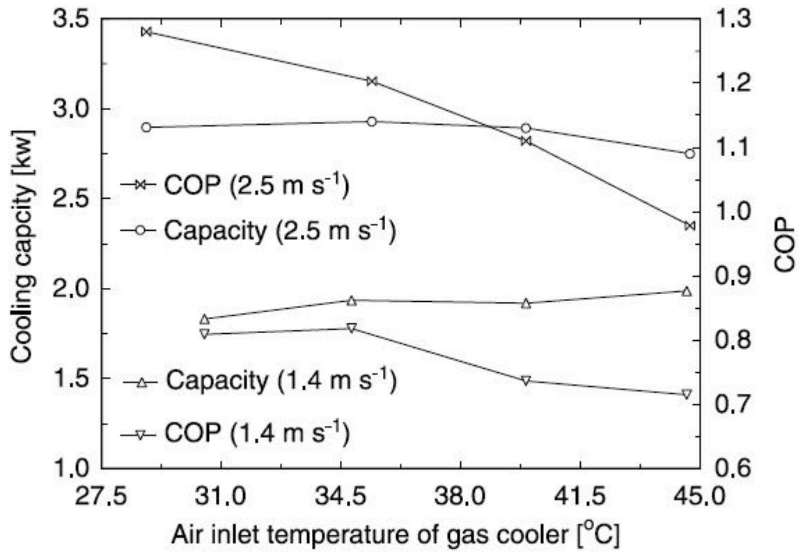

Figure 4. Comparison between cooling capacities, the COP and inlet air temperature in the Gas Cooler with variation of face speed of air in evaporator. (Liu et al, 2005),

Experimental results of researches in vehicles, considered as medium and high power, where comparisons were made between systems installed in vehicles using R-134a and CO_2. Figure 5 illustrates tests conducted in a vehicle, model BMW 3 series, made by Mager et al. (2002). The most interesting results showed that with the use of CO_2, the time of cabin cooling was significantly reduced. It is important to note also that the time to reduce temperature of 60°C to the comfort level was 17 minutes for CO_2 system and 29 minutes for R134a system, and, while the air conditioning system operating with CO_2 took 58 minutes to reach the required temperature (very cold), the system with R134a did not reach the same condition. Similar results were obtained for two others models, Audi and Mercedes-Benz, and also the results showed a reduction in the fuel consumption when air conditioning system operated with CO_2.

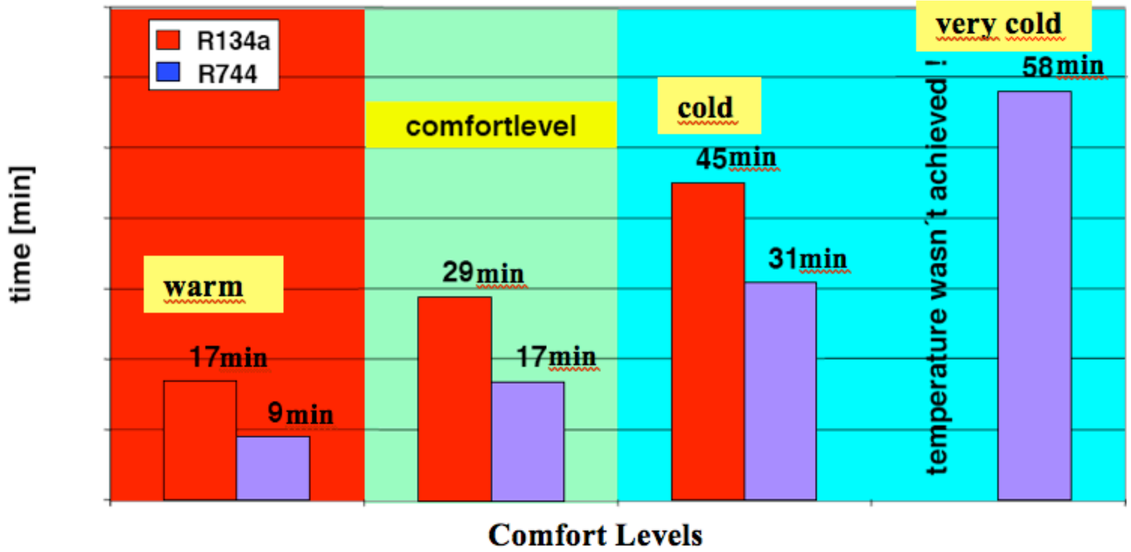

Figure 5. Comparison between the time of cabin cooling and comfortable zone in a BMW 3 vehicle. Mager et al. (2002).

New tests were performed in a car with small power, called popular cars, as 1000 cm^3. Results, obtained by Wieschollek and Heckt (2007) were quite encouraging, showing that the vehicle with CO_2 air conditioning system also had the time of cabin cooling reduced, fuel consumption was lower and the Coefficient of Performance, COP, also proved to be better than the system with R-134a. The tests were performed, even with different temperatures, varying between 10 and 45°C and showed a higher fuel consumption of vehicle equipped with R-134a in all temperatures tested, with an average of 0.4 liters per 100 km, as shown the Figs. 6 and 7.

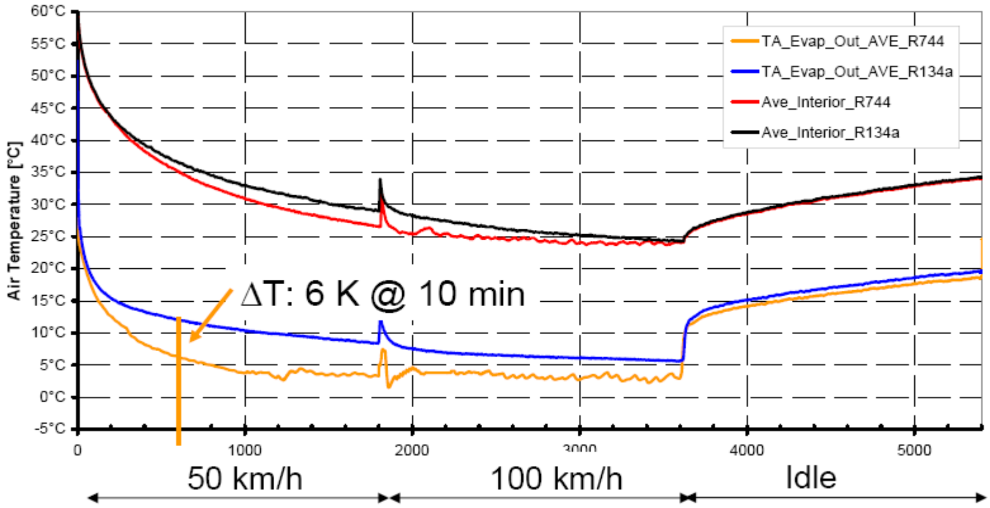

Figure 6. Comparison of time of cabin cooling and air exit of evaporator in a small vehicle.

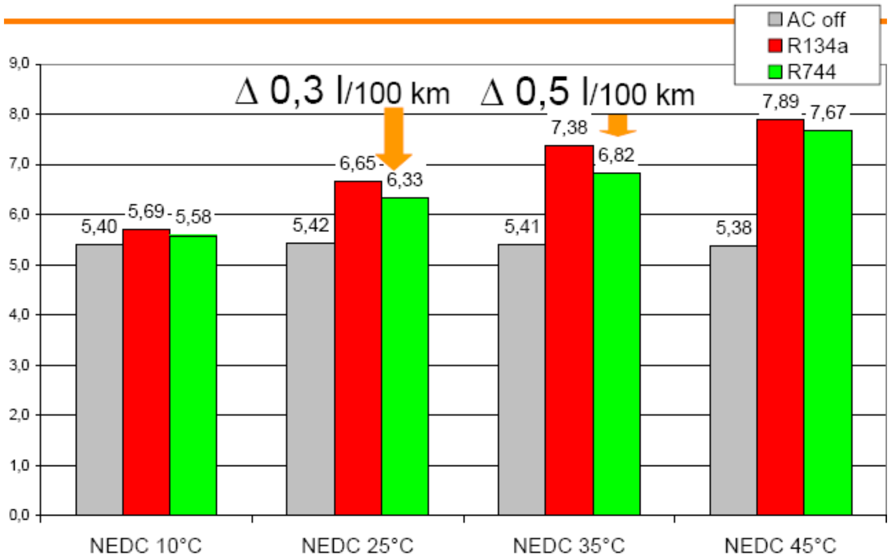

Figure 7. Comparison of fuel consumption in function of the temperature in a small vehicle.

The results for R-152a, working in a secondary loop, in comparison with R-134a system are presented in the Fig. 8. It is interesting to observe that the system operating as a reference, R-134a, presents the initial cooling time faster, 5 minutes, in relation to the R-152a system. It is also possible to affirm that the system operating with R-152a followed the reference system (R-134a) in all range of velocities. This study was made by Ghodbane and Fernqvist (2003).

One of the only studies found in the open literature on the thermal performance of the HFO-1234yf was conducted by Benouali et al. (2008). The tests were performed with ambient temperature of 45^{o}C and 40% of relative humidity, with air recirculation, as shown in the Fig. 9. The results showed that the vehicle with the R-134a air conditioning system presented better efficiency that the other vehicle with the HFO-1234yf air conditioning system in all velocities range, idle, 40 km/h and 90 km/h. The measured temperature in the outlet air diffuser with the R-134a air conditioning system reached 6.7^{o}C, while the air conditioning system with the refrigerant HFO-1234yf reached 8.3^{o}C, for velocity of 40 km/h. It is important to note that for this velocity the both systems delay 30 minutes to achieve the mentioned values. The energy efficiency was the same value when the velocity was 90 km/h.

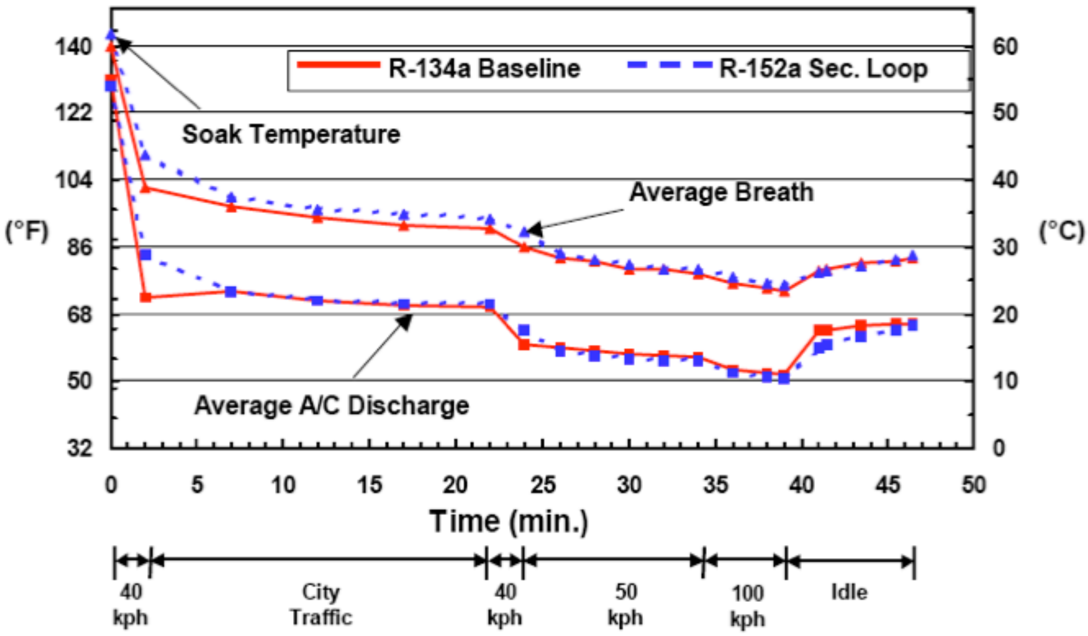

Figure 8. Comparison between R-134a and R-152a air conditioning systems in different test conditions, with ambient temperature of 46^{o}C and 25% of humidity. Ghodbane and Fernqvist (2003).

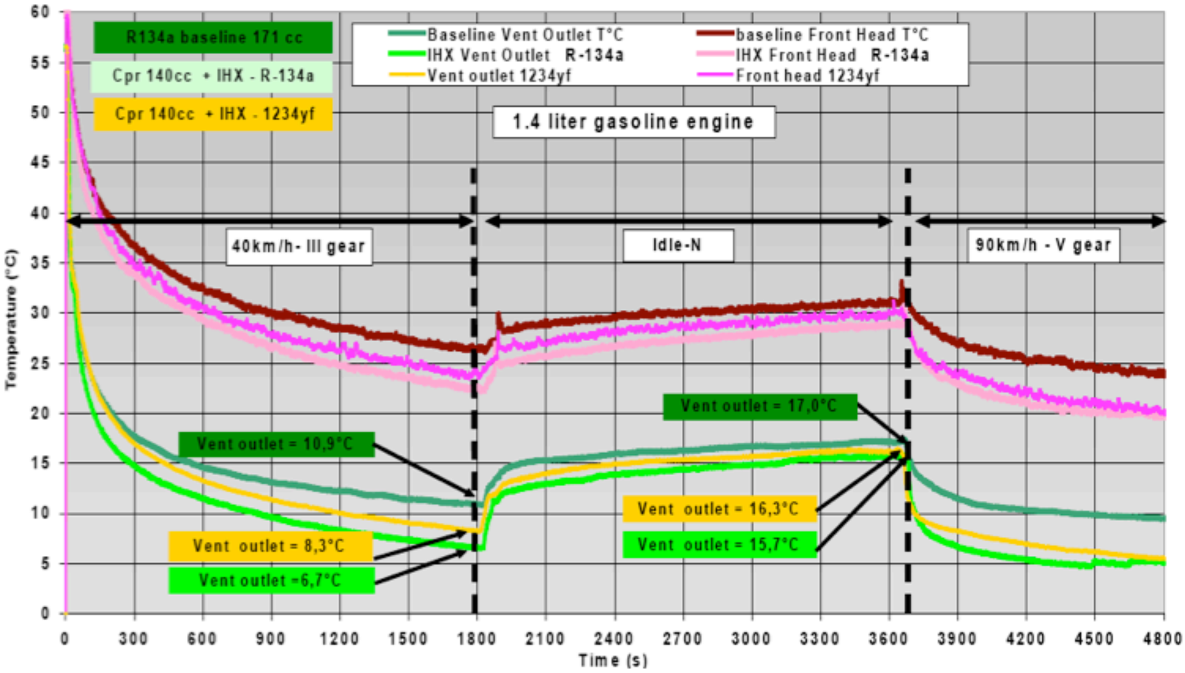

Figure 9. Comparison between R-134a and HFO-1234yf air conditioning systems in different test conditions, with ambient temperature of 45°C and 40% of humidity. Benouali et al. (2008)

3. CONCLUSIONS

The present paper showed many possibilities of alternative refrigerants to replace the HFC-134a in automotive air conditioning systems, such as HFC-152a, HFO-1234yf and CO_2. In relation to R-152a, it will be only possible in secondary loop and has a disadvantage of higher weight of full system and this refrigerant is flammable. The HFO-1234yf has an advantage in terms of global warming potential, with GWP value of 4, and short lifetime in atmosphere, 11 days. Also, this fluid has a compatibility with the actual technology used in currently automotive air conditioning systems. The disadvantage of this new compound is the flammability, lower than R-152a, however put in risk the occupants in case of a car collision.

Several researches, since the end of nineties, already showed the potential for the use of CO_2 as fluid in air systems conditioning and new automotive technologies are being continuously proposals. Such advantages are related to better performance of the CO_2 in comparison with the R134a in respect to the time of cabin cooling faster and better efficiency in more than 90% of driving conditions. The disadvantages of the CO_2 system are the high initial costs, since the CO_2 works with high pressures and also the new designs to adapt this new system.

As final comment, it is important to emphasize that CO_2 already has developed technology for use in automotive air conditioning systems, which leads to conclude that CO_2 is a very good alternative, since the manufacturers decide to invest in new designs. The HFO-1234yf can be an intermediary fluid, meanwhile the manufacturers will adapt up to 2017.

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