# A PERSPECTIVE ON R&D&I ACTIVITIES IN THE BRAZILIAN MOBILE AIR CONDITIONING MARKET

**Diogo Lôndero da Silva[1], diogo.londero@ufsc.br**
**Cláudio Melo[2], melo@polo.ufsc.br**
[1]Federal University of Santa Catarina, Joinville-SC, Brazil.
[2]POLO - Federal University of Santa Catarina, Florianópolis-SC, Brazil.

***Abstract.*** *In the past decades, it has been observed a remarkable increase in the global production of vehicles. This situation is more noticeable in developing countries, like Brazil, where the annual production of cars has almost quadrupled since 1990. Many of these automobiles are equipped with mobile air-conditioning (MAC) systems in order to improve the comfort and security of the vehicle occupants. In contrast to these positive characteristics, the MAC systems are also responsible for greenhouse gas emissions and an average increase of 7.5% on the fuel consumption. Due to environmental regulations, and vehicular efficiency programs, the automotive industry has been researching alternative fluid refrigerants and new technologies to minimize the environmental impact of MAC systems. Considering this scenario, the aim of this paper is to review the main features of MAC systems currently in use and identify the main Research and Development and Innovation (R&D&I) activities related to MAC systems that can be used on the Brazilian Market. The literature review indicates that energy efficiency improvements can be obtained by more efficient compressors, high performance heat exchangers, reduction of passenger cabin thermal load, design based on the thermal comfort analysis, improvements based on alternative cycles and reutilization of the waste heat.*

***Keywords****: Mobile air-conditioning, Energy efficiency, Automotive industry, Brazilian MAC system market.*

## 1. INTRODUCTION

According to ANFAVEA (2016) the total number of cars produced per year in Brazil has increased from 665,000 to 2.0 million units between 1990 and 2015, reaching a maximum of 2.9 million units in 2010. Currently, there are twenty three vehicle manufactures in operation in Brazil, among which fifteen are car manufactures. When compared to other vehicles companies, for instance, buses, trucks and light commercial vehicles, the car manufactories are responsible for more than 80% of the Brazilian total production. Due to the Brazilian tropical weather, a considerable number of these cars are sold with mobile air-conditioning (MAC) systems. It is estimated that 70% of the cars assembled in Brazil have factory-installed air conditioning systems (Denso, 2016).

Bhatti (1999) shows that the North American company Packard Motor Car developed the first complete air-conditioning system for summer and winter weathers in 1939. The main components of this system are illustrated in Figure 1. Although, in 1959, the number of cars equipped with air conditioning systems has already reached the mark of 1 million units in United States of America, this accessory only began to be commercialized in Brazil in the 60s. It has been reported that the first car equipped with a MAC system in Brazil was the Willys Itamaraty (Ruffo, 2015).

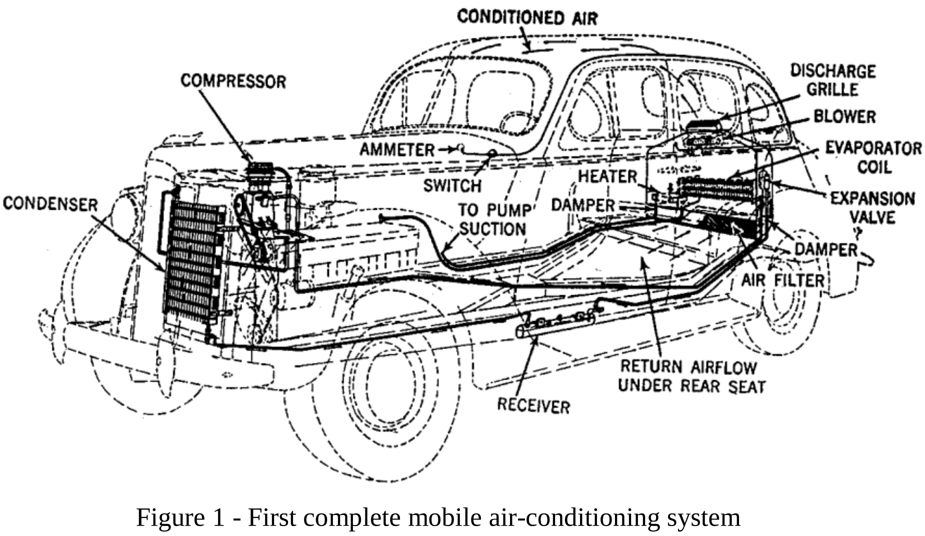



Figure 1 - First complete mobile air-conditioning system
(Source: Anon, 1930)

In addition to the safety considerations such as defogging and de-icing the windows, the second most important function of the MAC system is to provide comfort to the occupants. The MAC system is designed to be efficient, compact and operate in a wide range of conditions, (Jabardo et al., 2002). Surveys such as that conducted by Shah (2009) have shown that there are two main concepts of MAC systems in use in the car industry: (i) the thermostatic expansion valve receiver-dryer (TXV-RD) and (ii) the orifice tube accumulator-dryer (OT-AD). Figure 2a illustrates a TXV-RD system in which the cycle starts with the compression of the fluid refrigerant in the vapor state that exits the evaporator. During the compression process, the temperature of the vapor refrigerant is increased above the surroundings. Then, the super-heated refrigerant that exits the compressor flows to the condenser and transfers heat to the surroundings in order to become liquid. The high pressure liquid is accumulated in the receiver-dryer that removes moisture and allows only liquid refrigerant flows to the thermostatic expansion valve. Next, the liquid refrigerant expands through the thermostatic valve that regulates the mass flow rate according to the refrigerant superheat measured at the evaporator exit. Finally, the two-phase low pressure refrigerant that exits the thermostatic expansion valve flows through the evaporator, exchanges heat with the external air flow and returns to the initial thermodynamic state of the cycle. While the air flows through the external side of the evaporator its temperature and humidity are reduced. The cold and dry air the exits the evaporator is then circulated to the passenger compartment.

In contrast to the TXV-RD configuration, the orifice tube accumulator-dryer (OT-AD) concept, depicted in Figure 2b, uses an orifice-tube as expansion device and an accumulator-dryer in the exit of the evaporator. As the orifice-tube has a fixed internal obstruction, it is not able to adjust the refrigerant mass flow rate according to the evaporator thermal load. Thus, the use of an orifice-tube allows the compression of liquid refrigerant by the compressor if an accumulator-dryer is not installed in the exit of the evaporator. To protect the compressor, the accumulator-dryer is designed in such a way that only vapor refrigerant can flow to the compressor.

A TXV-RD system has a better energy performance than an OT-AD because (i) the thermostatic valve controls the refrigerant superheat at the exit of the evaporator and (ii) the accumulator dryer increases the pressure drop in the entrance of the compressor which decreases the compressor volumetric efficiency. However, the OT-AD concept is still widely used due to its low cost in comparison to the TXV-RD.

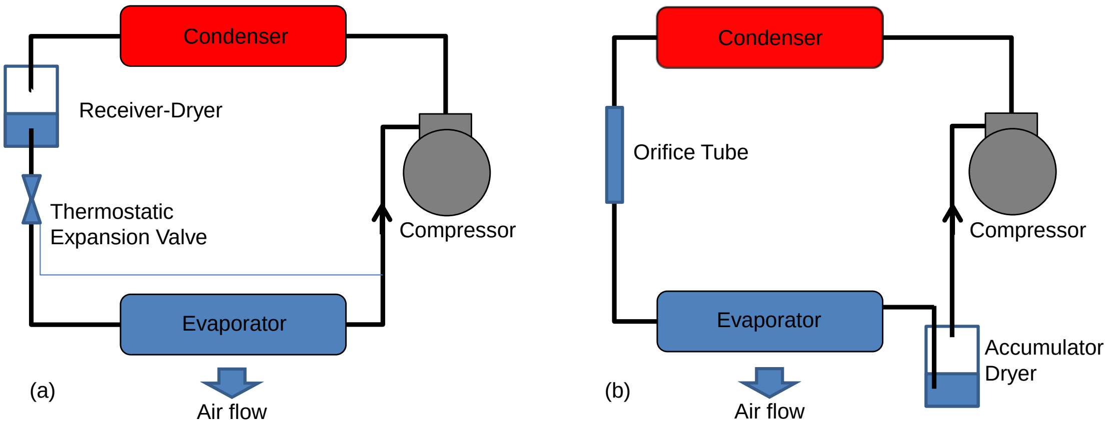



Figure 2 – Main MAC systems concepts

## 2. FLUID REFRIGERANTS

Fluid refrigerants are substances used to promote the heat transfer process in the hot and cold sides of the refrigeration system. The choice of a substance as a refrigerant is limited by its toxicity, flammability, cost, environmental impact and chemical stability (Goseny, 1982). The R-12 was the first substance used in large scale in the automotive industry as a fluid refrigerant. Although it is nontoxic and not flammable, in 1974, the R-12 was identified as one of the substances responsible for the ozone layer depletion.

The MAC systems are not hermetic and, consequently, their fluid refrigerant charge constantly leaks to the environment. It is estimated that ten percent of the refrigerant used in cars escapes every year due to maintenance operations, disposal and accidents (EC, 2013). For these reasons, international regulatory challenges were imposed to the MAC industry and, in the 1990s, the refrigerant R-12 started to be replaced by R-134a that was considered environmental friendly at that time. This change was impactful for the automotive industry and obligated it to develop new components compatibles with R-134a.

Years later, it was discovered that R-134a was related to the global warming. As a result, this refrigerant was included in the list of substances that Kyoto protocol aims to phase out in the near future. Many scholars hold the view that the mobile air-conditioning segment accounts for one third of total greenhouse gas emissions related to the air-conditioning and refrigeration segment (Rave and Goetzke, 2013). In 2014, the European Union stablished a regulation in which the use of GWP gases will be cut by two-thirds by 2030 compared with 2014 levels (EC, 2013). These events started a new debate on the refrigeration industry in order to identify alternative refrigerants. Currently, the main alternatives for R134a with low GWP are the refrigerants R-152a, R-1234yf and $CO_2$ (Bandarra Filho and Mendonza, 2010). Some characteristics of these three refrigerants are presented in sequence.

The R-152a has similar operating characteristics to R-134a and shows a better cooling performance. The main drawback of R-152a is the high flammability. Due to security restrictions, a possible way to use it in cars is in indirect systems, in which the R-152a flows in an isolated circuit located in the engine compartment that is in thermal contact with a secondary fluid that refrigerates the passenger's cabin (Shah, 2009).

$CO_2$ has been investigated mainly by Europeans laboratories and car manufactures, like Mercedes Benz and BMW. The advantages of $CO_2$ are: (i) it has a low GWP equivalent to 1, (ii) it is not flammable and (iii) it has a high cooling capacity that allows a fast cooling cabin when compared to R-134a. The main drawbacks related to $CO_2$ are (i) the relative high operation pressures and (ii) the low critical point that decreases the system COP when the environmental temperature is higher than 31°C (Tamura et al. 2005).

The third alternative is R-1234yf that has a low GWP equivalent to 4 in 100 years. Due to the similarity between the thermodynamics properties of R-1234yf and R-134a, the R-1234yf is considered a good drop-in replacement refrigerant for R-134a. A research developed by Babiloni et al. (2014) showed that, in comparison to R-134a, the use of R-1234yf reduces the system COP in 7%. The authors also showed that this difference can be reduced by the use of an internal heat exchanger in the MAC system. The main disadvantage of R-1234yf is its flammability. Although it has been reported that HFO-1234yf is safe refrigerant, as showed by Minor et al., (2010), it is still not clear for some car manufactures if it is secure substance for the cabin occupants of a vehicle.

The literature review also shows that the phase out of R-12 brought learnings to the automotive industry because it was a very expensive operation and did not solve the environmental problem completely. For these reasons, it is known that the choice of a new refrigerant is a complex decision that will inevitably require intense activities of research, development and innovation in the automotive and MAC system industries.

## 3. ENERGY EFFICIENCY

Farther to the direct emission of greenhouse gases to the environment, the MAC systems are also responsible for the indirect emission of $CO_2$ due to the fuel consumption required to drive the compressor and carry the additional weight of the system itself. Basically, a MAC system is driven by two mechanisms: (i) the transfer of power to the compressor through a belt coupled to the engine and (ii) the electrical power supplied by the battery used by the fans and the control system (IPCC, 2016).

It has been reported that 70% emissions from MAC systems are direct emissions. Farrington and Rugh (2000), estimate that, annually, 248 liters of gasoline are required to operate each MAC system. This represents an average increase up to 7.5% in the fuel consumption of a car that can be even higher when the MAC system is installed in compact models (Shah, 2009).

Due to environmental concerns, the Brazilian car manufactures have been pressured by governmental regulations to produce more efficient and less pollutant cars. These regulations establish pollutant emissions limits for different classes of automobiles (Civil, 2016). In addition, INMETRO has stablished the Vehicular Labeling Program that compares the energy efficiency of Brazilian vehicles. The test procedures used in this program considers real conditions found in the traffic jams and high speed in highways. The Vehicular Labeling Program also takes in account the use of the air-conditioning system to evaluate the total fuel consumption of the car (INMETRO, 2016). As the operation of air-conditioning systems significantly reduces the energy efficiency of a vehicle, it is important to identify strategies and technologies to improve the energy performance of the MAC system.

## 4. R&D&I ACTIVITIES IN THE BRAZILIAN MOBILE AIR-CONDITIONING MARKET

The previous literature review indicates three important issues related to the Brazilian mobile air-conditioning market: (i) a considerable number of cars equipped with MAC systems, (ii) a trend to phase-out the R-134a and (iii) the current automotive regulations for emissions and energy efficiency. Based on this facts, the following R&D&I activities have been identified as potential opportunities to be implemented in the Brazilian MAC system market.

### 4.1 High Efficiency Compressors

The main types of compressors used in the automotive industry are the fixed displacement, variable displacement, rotary and scroll (Shah, 2009). Due to cost restrictions the MAC systems are usually equipped with fixed-displacement compressors that are coupled to the car engine through a clutch. In this configuration, the compressor speed is proportional to the engine rotation. The fixed displacement compressor meets the air-conditioning demand with an on-off control strategy, which creates additional thermodynamic losses and disturbance to the engine. In this case, the refrigeration capacity is defined by the engine rotations instead of the thermal load, which in turn decreases the energy performance.

One alternative to avoid these problems is to use variable displacement compressors (VDC) that adjust the cooling capacity according to the cabin temperature. In the variable displacement compressor the pistons are driven by a wobble plate or a swash plate, as depicted in Figure 3. In this concept, the length of the piston stroke is determined by the angle of the plate. Therefore, a switch in the plate angle changes the length of the stroke, which varies the refrigerant mass flow. The plate angle is controlled by the refrigerant pressure in the compressor housing that is related to the variation of suction pressure and discharge pressure (Tian and Li, 2005).

Despite the additional cost, the use of variable displacement compressors have been increasing in the automotive air-conditioning systems due to the following advantages: it (i) eliminates the traditional on-off cycling of the compressor, (ii) improves the acoustic comfort inside the car, (iii) satisfies the various demands of air-conditioning and (iv) improves fuel economy (Nadamoto and Kubota., 1999 and Tian et al., 2004).

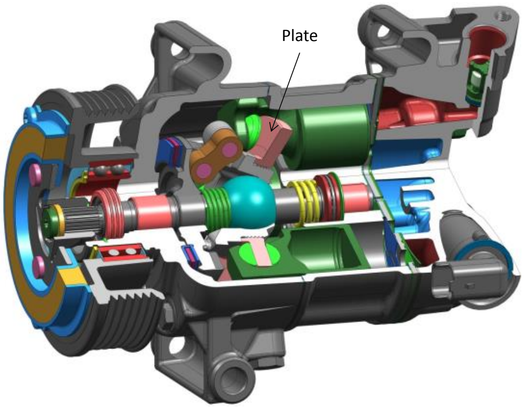



Figure 3 – Variable displacement compressor
(Source: Delphi, 2016)

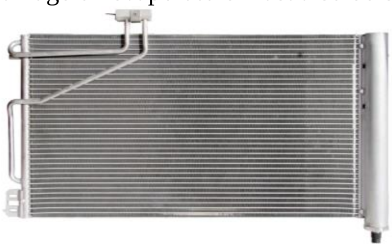
**4.2 High Performance Condensers and Evaporators**

In general, the fuel consumption of an air-conditioning system increases with the temperature difference between the air and the fluid refrigerant inside the heat exchangers. For this reason, the energy performance of a MAC system can be improved with the use of heat exchangers with high heat transfers rates, such as microchannels models, that reduces this temperature gradient (Qui et al., 2010).

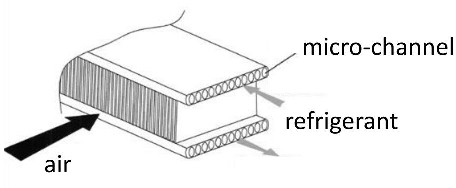
Microchannel heat exchangers are characterized by hydraulic diameter less than 1 mm. In addition to the high heat transfers rate, the use of microchannels heat exchangers is recommend in MAC system because they allow refrigerant charge reductions and are lighter and compact. Han et al. (2012) present a study about the recent developments on microchannels heat exchangers pointing out that there are opportunities to improve the efficiency of this kind of heat exchangers based on CFD techniques, use of different materials or the development of manufacturer processes. As the performance of microchannels heat exchangers are very related to the geometrical parameters there are also opportunities to apply optimization techniques during the heat exchanger design stage. One design goal is to identify the geometries that avoid local dry-out flows inside the microchannels.

Figure 4(a) shows a typical microchannel condenser used on MAC systems. As can be seen on Figure 4(b), this heat exchanger is comprised by extruded micro-channel tubes for the refrigerant flow on the internal side and corrugate multilouver fins for the air flow on the external side.

As the evaporator of a MAC system can operate in temperatures lower than the dew point, this component is subject to condensate retention. The moist surface can promote biological activity that results in odors and possible allergic reactions for the cabin occupants (Qi, 2013). This problem is exacerbated in humid tropical climates, like that of Brazil, resulting in high consumer's complaints rates. Therefore, the literature review shows that the water retention and drainage on evaporators must also be considered on the MAC design system.



(a)




(b)

Figure 4 – Micro-channel heat exchanger
(Source: Climetal, 2016)

### 4.3 Reduction of the thermal load of the vehicle using advanced glazings

Another strategy used to reduce the fuel consumption of MAC systems is to decrease the thermal load related to solar irradiation. This is an interesting approach in tropical countries like Brazil, where the solar irradiation reaches values up to 6.5 kWh/m$^2$ in the northeastern region (Martins et al. 2008).

The thermal load in the interior of vehicles can be reduced using spectrally selective glazing. This class of glazings is designed to reduce the transmissivity of ultraviolet and infrared solar irradiation to the passenger's cabin. Figure 5 compares the transmissivity of conventional and selective glazings for different wavelengths. As can be seen, the selective glazing effectively reduces the transmissivity for wavelengths higher than 900 nm. Farrington and Rugh (2000) reported that the thermal load of a car can be reduced up to 27% when a standard windshield is replaced with a model designed with spectrally selective glazing. Thus, there are evidences that selective glazings can be used to reduce the MAC system fuel consumption.

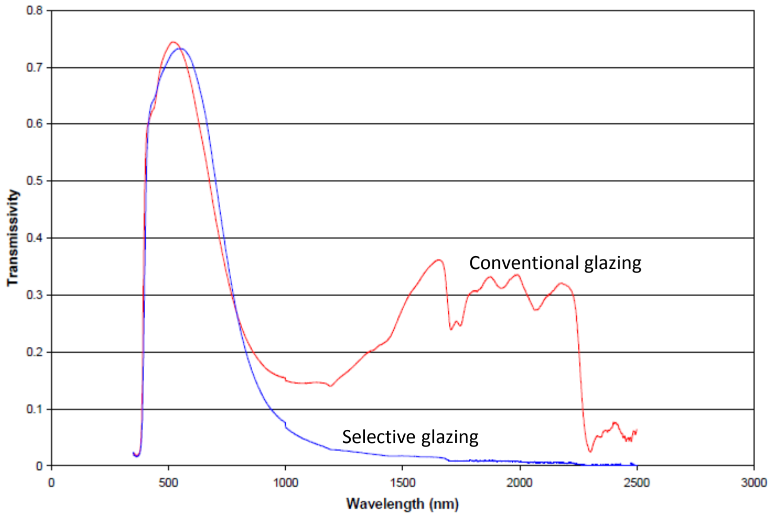



Figure 5 – Comparison of solar transmissivity
(Source: Farrington and Rugh, 2000)

### 4.4 Thermal comfort analysis

Recent studies show evidences of low occupancy rates in cars, indicating that the MAC system is often consuming more energy than required. To overcome this problem, the automotive industry is employing the thermal comfort analysis to design localized air-conditioning system in the passenger cabin. In this approach, the focus is on the comfort of the occupant and not on achieving a uniform temperature. This technique guaranties human thermal comfort for the occupants and avoid extra cooling on the vacant seats, which decreases the fuel consumption. Therefore, the thermal comfort has becoming an important issue in the automobile design (Croitoru et al., 2015).

Alahmer et al. (2011) reviewed the main theoretical and experimental approaches used to perform the thermal comfort analysis. It was identified that different indices can be used for this purpose, as the Predicted Mean Value (PMV) that classifies the thermal sensation in a scale of seven points. Although PMV index is widely employed, it is not accurate for non-homogenous temperature conditions that occur inside the passenger cabin. For this reason new models have been developed to consider real situations with thermal transients and gradients of temperature and air velocity. Figure 6 shows the use of CFD on a virtual manikin to evaluate the thermal comfort of humans in details and prevent extra cooling of the passenger cabin.

Oh et al. (2014) used a computational fluid dynamics (CFD) model to carry out a thermal comfort analyses of a medium size car. The average cabin air temperature was measured and compared with the simulations results with maximum differences of 2$^o$C. The CFD model was used to propose an optimized localized air-conditioning with the same thermal comfort of a conventional system. The energy consumption results of both systems were compared, when it was found up to 30% of energy saving for the localized air-conditioning.

Figure 6 – Use of CFD on thermal comfort analysis
(Source: Sorensen and Voigt, 2003)

### 4.5 Alternative refrigeration cycles

The MAC system performance can also be improved by alternative refrigeration cycles. For instance, Tuo and Hrnjak (2012) proposed the use of a flash gas bypass on automotive air-conditioning systems with microchannel evaporators. Figure 7 compares two air-conditioning cycles, in which one is operating in a (a) direct expansion mode and the other in a (b) flash gas bypass mode. As can be seen, the direct expansion mode guarantees that only liquid refrigerant is fed into the evaporator. The bypassed mass flow and its pressure line are controlled by a valve.

Figure 8 shows a comparison of infrared images of the same micro-channel evaporator operating in the direct expansion and flash gas bypass modes for different superheats at the compressor inlet. The red areas on the images indicate the presence of superheated refrigerant inside the evaporator. It is observed that the flash gas bypass mode provides a homogenous liquid refrigerant distribution in the evaporator inlet in comparison to the direct expansion mode. Moreover, the superheat region is reduced in the flash gas bypass when compared to the direct expansion mode.

The energy performance results of the conventional and proposed configurations were experimentally compared using the same microchannel evaporator. It was identified that the flash gas bypass mode increases the COP of the system about 37%-55% when the compressor speed was adjusted to maintain the same cooling capacity. This improvement was justified by two main reasons: (i) a more homogenous refrigerant distribution in the evaporator microchannels and (ii) a reduction on the refrigerant side evaporator pressure drop.

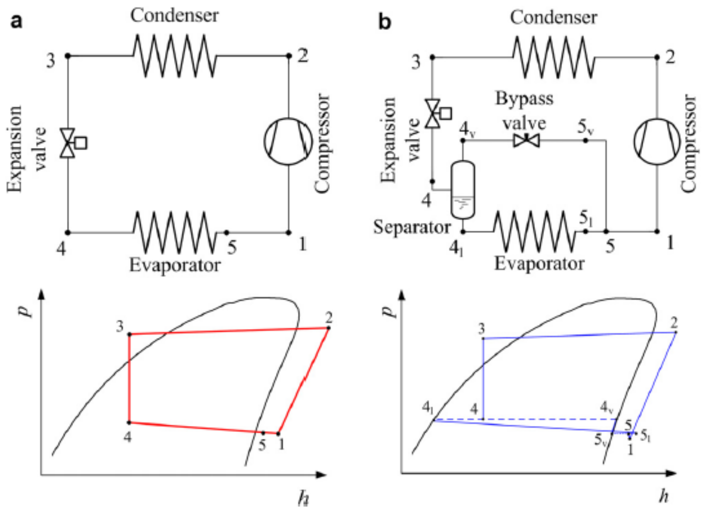



Figure 7 – System configuration and p-h cycle for the (a) Direct Expansion mode and (b) Flash Gas Bypass mode.
(Source: Tuo and Hrnjak, 2012)

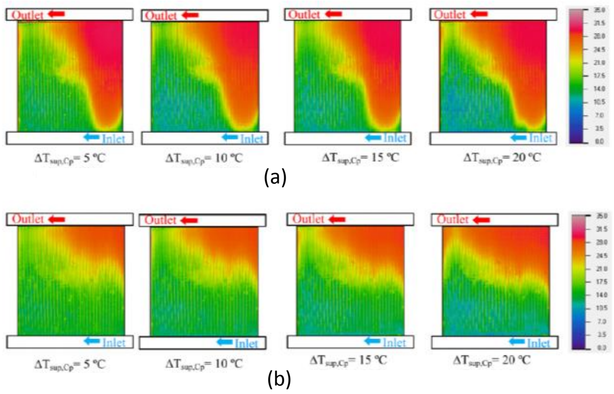



Figure 8 – Evaporator infrared images for the (a) Direct Expansion mode and (b) Flash Gas Bypass mode
(Source: Tuo and Hrnjak, 2012)

**4.6 Recovery of engine waste heat for reutilization in air-conditioning system**

One alternative to the conventional vapor compression system identified on the literature review is the absorption refrigeration system. This alternative system is attracting attention of the automotive industry because it can be driven by low-grade thermal energy rejected by the engine, with temperatures as low as 50°C. In addition, this system can operate with natural refrigerants like water or ammonia that are considered environmental friendly.

Wang and Vineyard (2011) shows that the fundamental adsorption cycle consists of four steps: (i) heating and pressurization, (ii) desorption and condensation, (iii) cooling and depressurization, and (iv) adsorption and evaporation. The cycle starts with the heating process of the adsorber by a heat source, which is analog to the compression in the vapor-compression cycle. In the second step, when the adsorber achieves a minimum temperature, the refrigerant vapor is desorbed and releases heat in the condenser to become liquid. In the third step, the adsorber must be disconnected from the condenser to be cooled by a secondary fluid. During this process, the adsorber pressure is reduced to the evaporating pressure, which is analog to the expansion process in the vapor-compression cycle. In the fourth step, the adsorber is connected to the evaporator to adsorb refrigerant vapor from the evaporator, which produces the cooling effect on the evaporator. Based on the process description it is verified that the adsorption refrigeration cycle is an intermittent process. For this reason, a continuous cooling effect can only be achieved with at least two adsorbers.

De Boer et al. (2009) developed a prototype of an automotive silicagel-water adsorption cooling system. Two reactors were used on this system in order to obtain a continuous cooling effect. The system was tested at different operational conditions and produced 2 kW of cooling capacity with a COP ranging of 0.3 – 0.5. After the laboratory tests the authors installed the prototype in a medium size car an obtained similar results. Although it was observed a lack in the efficiency and the cooling capacity of the prototype, this study demonstrated evidences that the waste heat can be used to drive an MAC system recovering the waste heat of the engine.

## 5. CONCLUSIONS

The mobile air-conditioning (MAC) system came into wide use, mainly in developed countries with hot climates. In Brazil, it is estimated that 70% of new cars produced have factory-installed MAC systems. This accessory promotes safety and comfort to the cabin passengers. However, the MAC systems are also responsible for direct greenhouse gas emissions and an average increase of 7% in the fuel consumption. In the last decades, the Brazilian government has stablished pollutant emission limits for cars. More recently, INMETRO created a Vehicular Labeling Program to compare the energy efficiency of different vehicles that considers the air-conditioning use. For these reasons, it is considered mandatory identify opportunities to improve the energy efficiency of MAC systems.

This study has found that there are two main concepts of MAC systems in use: (i) the thermostatic expansion valve receiver-dryer system (TXV-RD) and the (ii) orifice tube accumulator-dryer (OT-AD). A description of these two concepts and their components was presented and compared. It was identified that the TXV-RD provides a better COP than the OT-AD concept. Another important issue found is related to the development of climate-friendly fluid refrigerants to replace the R-134a. Currently, the main low GWP alternatives for R-134a are the refrigerants R-152a, $CO_2$ and R-1234yf. It was observed that the R-1234yf is a strong candidate for this purpose, but there are still some safety issues related to its flammability under investigation. It is also expected that the phase-out of R-134a will require great research and engineer efforts to develop components compatible with a new refrigerant.

This study has also identified the following technologies and strategies that can be used to increase the energy efficiency of the MAC systems used in Brazil: (i) use of variable capacity compressors, (ii) use of high performance heat exchangers, (iii) reduction of the thermal load of the vehicle using advanced glazings, (iv) design based on thermal analysis, (v) use of alternative cycles and (iv) recovery of engine waste heat for reutilization in air-conditioning system.

Therefore, the findings of this research provide insights for R&D&I activities that can be used by the national automotive manufacturers to improve the efficiency of MAC systems. These activities will not only promote the development of the national technology but also contribute to the formation of skilled professionals and more environmental friendly vehicles.

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