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

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Abstract. *Over the past few decades there has been a remarkable increase in the global production of vehicles. This is especially notable 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% in the fuel consumption. In order to comply with 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, this paper provides a review of the main features of MAC systems currently in use and identifies the main research, development and innovation (R&D&I) activities related to MAC systems which could be applied in the Brazilian market. The literature review indicates that energy efficiency improvements can be obtained by using more efficient compressors and high-performance heat exchangers, reducing the passenger cabin thermal load and introducing designs considering thermal comfort analysis and improvements based on alternative cycles and the reutilization of 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, of which fifteen are car manufactures. When compared to other vehicles companies, for instance, buses, trucks and light commercial vehicles, the car manufacturers are responsible for more than 80% of the total Brazilian production. Due to the tropical/subtropical climate in Brazil, 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) reports that the North American company Packard Motor Car developed the first complete air-conditioning system for summer and winter weather conditions in 1939. The main components of this system are illustrated in Figure 1. By 1959, the number of cars equipped with air conditioning systems had already reached 1 million units in the United States of America, but this accessory only began to be commercialized in Brazil in the 1960s. It has been reported that the first car equipped with an MAC system in Brazil was the Willys Itamaraty (Ruffo, 2015).

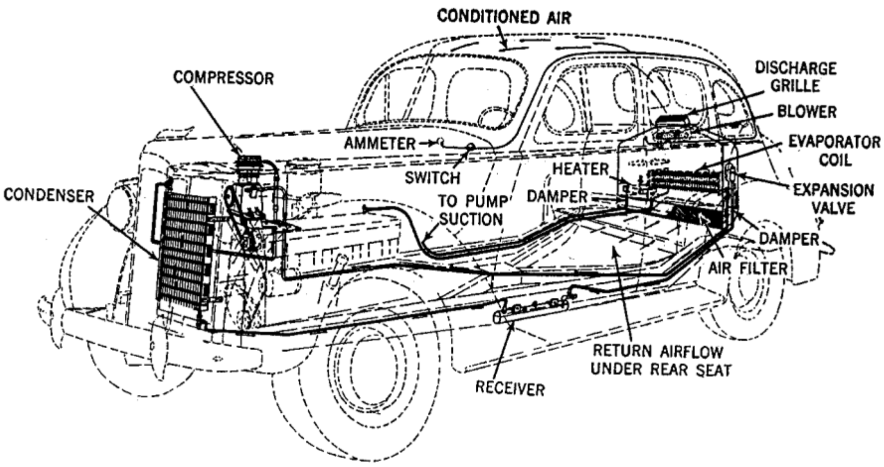


Figure 1 - First complete mobile air-conditioning system installed in a car
(Source: Anon, 1930)

In addition to the safety considerations such as the defogging and de-icing of 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 under 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 shows a TXV-RD system in which the cycle starts with the compression of the refrigerant fluid in the vapor state that exits the evaporator. During the compression process, the temperature of the refrigerant vapor is increased to a value above the temperature of the surroundings. 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, which removes moisture and allows only liquid refrigerant to flow to the thermostatic expansion valve. Next, the liquid refrigerant expands through the thermostatic valve, which 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 dry air which exits the evaporator is then circulated to the passenger compartment.

In contrast to the TXV-RD configuration, in the orifice tube accumulator-dryer (OT-AD) concept, depicted in Figure 2b, an orifice-tube is used as the expansion device and there is an accumulator-dryer at the exit of the evaporator. Since 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 at 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 at the entrance of the compressor, which decreases the volumetric efficiency of the compressor. However, the OT-AD concept is still widely used due to its low cost in comparison to the TXV-RD.

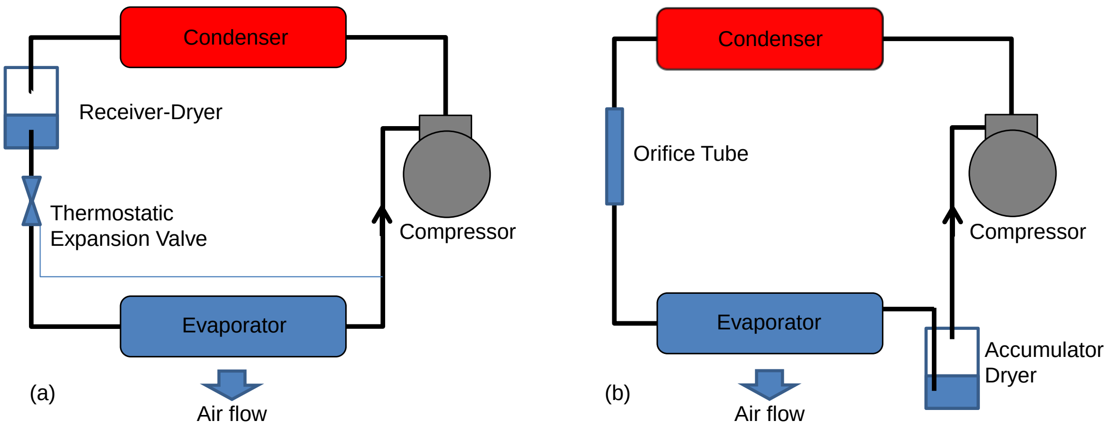


Figure 2 – Main concepts associated with MAC systems

2. FLUID REFRIGERANTS

Fluid refrigerants are substances used to promote the heat transfer process on 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 (Gosney, 1982). 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, R-12 was identified as one of the substances responsible for 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). Thus, international regulatory challenges have been imposed on the MAC industry and, in the 1990s, the refrigerant R-12 started to be replaced by R-134a, which was considered to be environmental friendly at that time. This change had a considerable impact on the automotive industry, obligating it to develop new components compatible with R-134a.

Years later, it was discovered that R-134a is related to global warming. As a result, this refrigerant was included in the list of substances named in the Kyoto protocol which are to be 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 2015, it was established a revised version of the European Union "F-gases" Regulation. This revised regulation includes a phase-down schedule of F-gases to reduce the use of these refrigerants in 75% by 2030 (IIR, 2015). These events triggered a new debate in the refrigeration industry with regard to identifying alternative refrigerants. Currently, the main alternatives to 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 described below.

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

CO_2 has been investigated mainly by European laboratories and car manufactures, for instance, 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 faster cabin cooling compared to R-134a. The main drawbacks related to CO_2 are (i) the relatively high operation pressures and (ii) the low critical point, which decreases the system COP when the ambient temperature is higher than 31°C (Tamura et al., 2005).

The third alternative is R-1234yf, which has a low GWP (equivalent to 4 over 100 years). Due to the similarity between the thermodynamic properties of R-1234yf and R-134a, R-1234yf is considered to be a good drop-in replacement refrigerant for R-134a. Research carried out by Babiloni et al. (2014) showed that, in comparison to R-134a, the use of R-1234yf reduces the system COP by 7%. The authors also reported that this difference can be reduced with 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 a safe refrigerant, as demonstrated by Minor et al. (2010), it is still not considered by some car manufactures that its use is safe for the occupants of a vehicle cabin.

The literature review also revealed that the automotive industry gained valuable experience from the phase out of R-12, because it was a very expensive operation and did not solve the environmental problem completely. Thus, it is known that the choice of a new refrigerant is a complex decision that will inevitably require intense research, development and innovation activities in the automotive industry and by companies which design MAC systems.

3. ENERGY EFFICIENCY

Besides the direct emission of greenhouse gases to the environment, 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% of emissions from MAC systems are direct emissions. Farrington and Rugh (2000), estimate that 248 liters of gasoline are required annually to operate each MAC system. This represents an average increase of up to 7.5% in the fuel consumption of a car, and this figure could 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 polluting cars. These regulations establish pollutant emission limits for different classes of automobiles (Civil, 2016). In addition, INMETRO has stablished the Vehicular Labeling Program, which compares the energy efficiency of Brazilian vehicles. The test procedures used in this program consider real conditions found in traffic jams and at high speed on highways. The Vehicular Labeling Program also takes in account the use of the air-conditioning system to evaluate the total fuel consumption of a 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 MAC systems.

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

The above literature review highlights three important issues related to the Brazilian mobile air-conditioning market: (i) a considerable number of cars are equipped with MAC systems, (ii) there is a trend toward the phasing out of R-134a and (iii) automotive emissions and energy efficiency are governed by current regulations. In this context, the following R&D&I activities have been identified as providing potential opportunities for improvements to be implemented in the Brazilian market for MAC systems.

4.1 High-Efficiency Compressors

The main types of compressors used in the automotive industry are 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 (VDCs) that adjust the cooling capacity according to the cabin temperature. In VDCs the pistons are driven by a wobble plate or a swash plate, as shown 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, which is related to the variation in the suction pressure and discharge pressure (Tian and Li, 2005).

Despite the additional cost, the use of VDCs in automotive air-conditioning systems has been increasing due to the following advantages: they (i) eliminate the traditional on-off cycling of the compressor, (ii) improve the acoustic comfort inside the car, (iii) satisfy the various demands for air-conditioning, and (iv) improve fuel economy (Nadamoto and Kubota., 1999 and Tian et al., 2004).

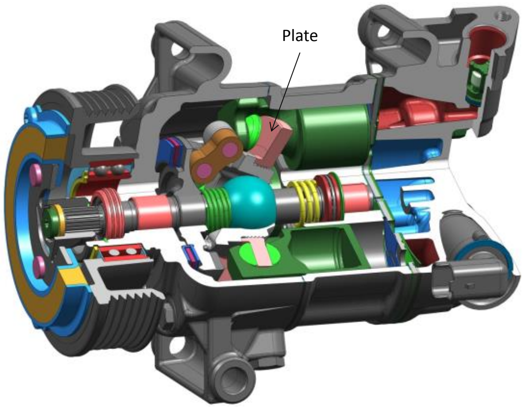


Figure 3 – Variable-displacement compressor
(Source: Delphi, 2016)

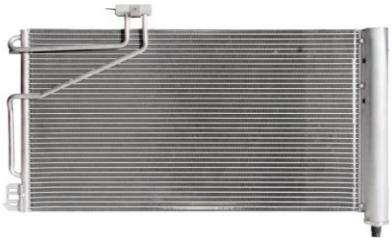
4.2 High-Performance Condensers and Evaporators

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. Thus, the energy performance of an MAC system can be improved with the use of heat exchangers with high heat transfer rates, such as microchannel models, which reduces this temperature gradient (Qui et al., 2010).

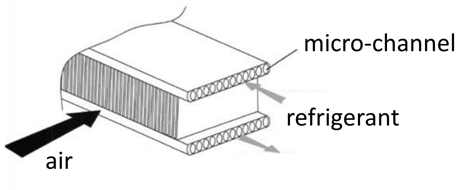
Microchannel heat exchangers are characterized by hydraulic diameters of less than 1 mm. In addition to the high heat transfer rate, the use of microchannel heat exchangers is recommend in MAC system because they allow refrigerant charge reductions and are lighter and more compact. Han et al. (2012) reported a study on recent developments related to microchannel heat exchangers, pointing out that there are opportunities to improve the efficiency of this type of heat exchangers based on computational fluid dynamics (CFD) techniques, the use of different materials or the development of new manufacturer processes. Since the performance of microchannel heat exchangers is strongly 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 in MAC systems. As can be seen in Figure 4(b), this heat exchanger is comprised of extruded micro-channel tubes for the refrigerant flow on the internal side and corrugated multilouver fins for the air flow on the external side.

Since the evaporator of a MAC system can operate at 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 in the cabin occupants (Qi, 2013). This problem is exacerbated in humid tropical climates, like that of Brazil, resulting in high consumer complaint rates. Therefore, the literature review shows that the water retention and drainage of evaporators must also be considered in the MAC system design.



(a)



(b)

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

4.3 Reduction in the thermal load of a vehicle using advanced glazing

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 inside vehicles can be reduced by using spectrally selective glazing. This class of glazing is designed to reduce the transmission of ultraviolet and infrared solar irradiation to the passenger cabin. Figure 5 compares the transmissivity of conventional and selective types of glazing 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 by up to 27% when a standard windshield is replaced with a model designed with spectrally selective glazing. Thus, there are evidences that selective glazing can be used to reduce the fuel consumption associated with MAC systems.

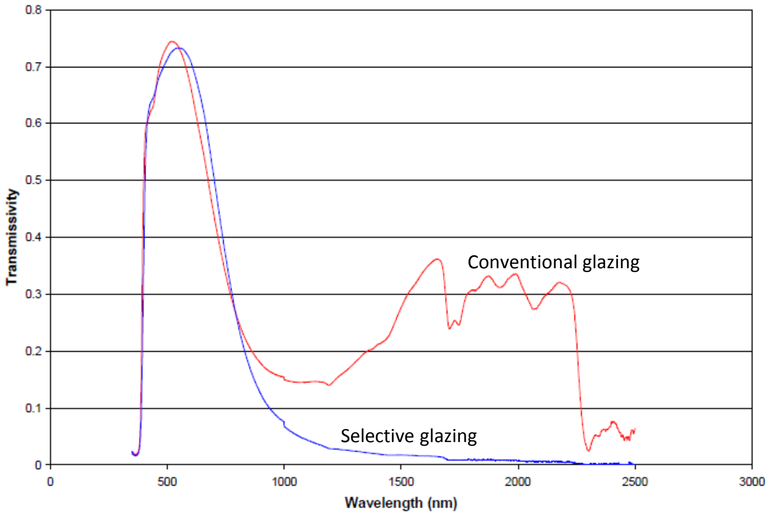


Figure 5 – Comparison of solar transmissivity
(Source: Farrington and Rugh, 2000)

4.4 Localized cooling for human comfort

Recent studies show evidence of low occupancy rates in cars, indicating that the MAC system often consumes more energy than required. To overcome this problem, the automotive industry is employing 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 guarantees human thermal comfort for the occupants and avoids extra cooling for the vacant seats, which decreases the fuel consumption. Therefore, thermal comfort has become an important issue in automobile design (Croitoru et al., 2015).

Alahmer et al. (2011) reviewed the main theoretical and experimental approaches used to perform thermal comfort analysis. It was identified that different indices can be used for this purpose, such as the Predicted Mean Value (PMV), which classifies the thermal sensation according to a scale of seven points. Although the PMV index is widely employed, it is not accurate for the 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 temperature and air velocity gradients. Figure 6 shows the application of CFD using a virtual manikin to evaluate the thermal comfort of humans in detail and prevent extra cooling of the passenger cabin.

Oh et al. (2014) used a CFD model to study the thermal comfort inside a medium-sized car. The average cabin air temperature was measured and compared with the simulation results with maximum differences of 2°C. The CFD model was used to propose an optimized localized air-conditioning system with the same thermal comfort as a conventional system. The energy consumption results for the two systems were compared and energy savings of up to 30% were found for the localized air-conditioning.

Figure 6 – Use of CFD in 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 in automotive air-conditioning systems with microchannel evaporators. Figure 7 compares two air-conditioning cycles, one operating in a (a) direct expansion mode and the other in a (b) flash gas bypass mode. As can be seen, the flash gas bypass cycle ensures that only liquid refrigerant flows to 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 superheating conditions at the compressor inlet. The red areas on the images indicate the presence of superheated refrigerant inside the evaporator. It can be observed that the flash gas bypass mode provides a homogenous liquid refrigerant distribution at 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 for 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 by around 37%-55% when the compressor speed was adjusted to maintain the same cooling capacity. This improvement is attributable to two main factors: (i) a more homogenous refrigerant distribution in the evaporator microchannels and (ii) a reduction in the refrigerant side evaporator pressure drop.

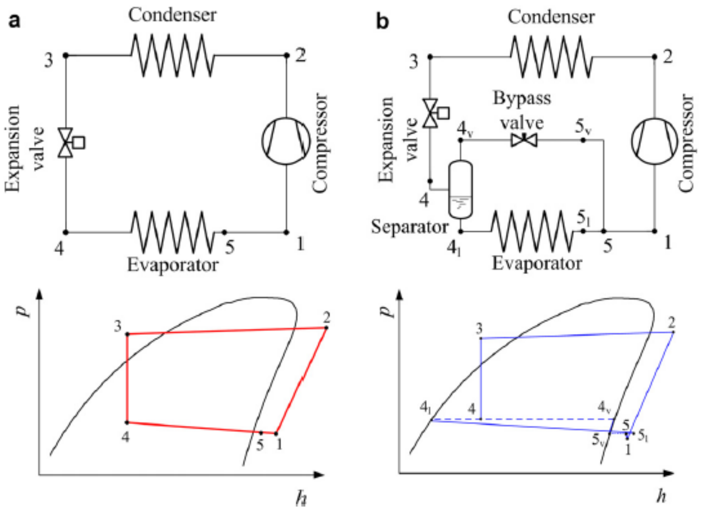


Figure 7 – System configuration and p-h cycle for the (a) Direct Expansion mode and (b) Flash Gas Bypass mode
(Source: Tuo and Hrnjak, 2012)

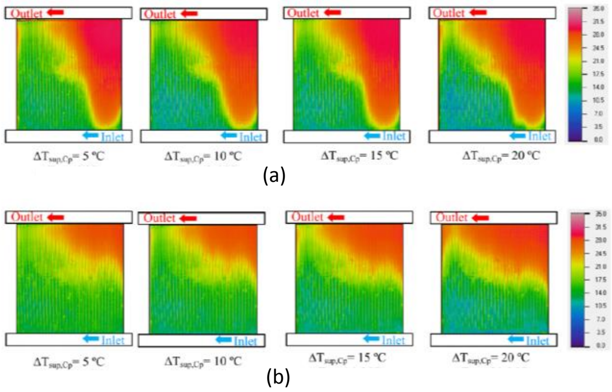


Figure 8 –Infrared images of the evaporator for the (a) Direct Expansion mode and (b) Flash Gas Bypass mode
(Source: Tuo and Hrnjak, 2012)

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

One alternative to the conventional vapor compression system identified in the literature review is the adsorption refrigeration system. This type of system is attracting the 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, such as water.

As described by Wang and Vineyard (2011), 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 of the adsorber by a heat source, which is analogous 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 analogous 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 a cooling effect on the evaporator. Based on the process description, it is verified that the adsorption refrigeration cycle is an intermittent process. Thus, 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 in this system in order to obtain a continuous cooling effect. The system was tested under different operational conditions and produced 2 kW of cooling capacity with a COP ranging from 0.3 to 0.5. After the laboratory tests the authors installed the prototype in a medium-sized car and obtained similar results. Although the efficiency and the cooling capacity of the prototype were poor, this study provided evidence that the waste heat recovered from the engine can be used to drive an MAC system.

5. CONCLUSIONS

Mobile air-conditioning (MAC) systems are widely used, 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 for the cabin passengers. However, MAC systems are also responsible for direct greenhouse gas emissions and an average increase of 7% in the fuel consumption. Over the past few decades, the Brazilian government has established pollutant emission limits for cars. More recently, INMETRO created a Vehicular Labeling Program to compare the energy efficiency of different vehicles, which considers the use of air-conditioning. Thus, it is considered mandatory to identify opportunities to improve the energy efficiency of MAC systems.

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

In addition, the following technologies and strategies which can be used to increase the energy efficiency of MAC systems used in Brazil were highlighted by this review: (i) use of variable capacity compressors, (ii) use of high-performance heat exchangers, (iii) reduction in 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 systems.

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

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