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Automotive Air-Conditioning Systems—Historical Developments, the State of Technology, and Future Trends

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Automotive air-conditioning (A/C) or mobile air-conditioning (MAC) systems have played an important role in human comfort and to some extent in human safety during vehicle driving in varied atmospheric conditions. It has become an essential part of the vehicles of all categories worldwide. After discussing the basic operation of the A/C system, a brief summary is provided on historical development of the vehicular A/C system, with refrigerant history from the inception of the A/C system to future systems: R12, R134a, and enhanced R134a A/C system, and next-generation refrigerants having no ozone depletion potential in the stratosphere and global warming potential less than 150. The discussion also includes an enhanced MAC system with R134a, and the direct and indirect emissions from vehicles impacting global warming due to the use of the A/C system. This would explain why we continue to change the refrigerants in the automotive A/C system in spite of billions of dollars of cost for the previous refrigerant change (from R12 to R134a). The system design considerations are then outlined for minimizing the impact of A/C operation on the vehicle fuel consumption. Finally, new concepts of design of A/C system and vehicle heat load reduction ideas are discussed to further minimize the impact of A/C system operation on the environment without impacting human comfort. It is anticipated that this article will provide the overall and detailed prospective of the A/C system developments and provide an opportunity to the researchers to accelerate research and development for the refrigerant changeover and A/C system and component optimization and cost reduction.

INTRODUCTION

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), air conditioning (A/C) is the science of controlling the temperature, humidity, motion, and cleanliness of air within an enclosure. In a passenger/driver cabin of a vehicle, air conditioning means a controlled and comfortable environment in the passenger cabin during summer, winter, and rainy seasons, i.e., control of temperature (for cooling or heating), control of humidity (decrease in passenger cabin humidity), control of air circulation and ventilation (amount of air flow and fresh air intake vs. partial or full recirculation), defrost or defogging of the windshield, and cleaning of air from odor, pollutants, dust, pollen, etc. before entering the passenger cabin.

While the A/C system provides comfort to the passengers in a vehicle, its operation in a vehicle has twofold impact on fuel consumption and subsequently on indirect tailpipe CO_2 (indirect greenhouse gas [GHG] emissions): (1) burning extra fuel to power the compressor for the A/C operation, and (2) carrying extra A/C component weight in the vehicle all the time, whether the A/C is on or off. In addition, direct refrigerant emissions (system leakage, vehicle accidents, and losses at service and scrap) impact the GHG emissions. Also, the total operation time of the A/C system (to impact item 1) depends on the climatic condition of the concerned geographical region and the time of the year. The most important impact on the fuel consumption is

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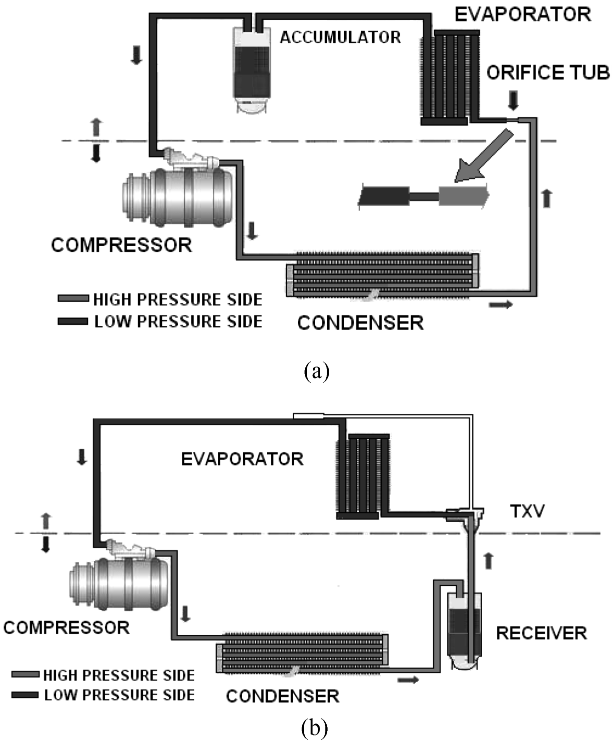
when the A/C is running. Clodic [1] reported the additional fuel consumption due to mobile air-conditioning (MAC) operation as 2.5–7.5% (in the United States/Europe), considering the climatic conditions, engine type (diesel or gasoline), and user profile. Corresponding CO_2 emission due to MAC operation is between 150 and about 500 kg annual CO_2 equivalent per year per vehicle in developed countries. The impact on the fuel consumption is somewhat more significant (maybe 10% or more) when the A/C is installed in compact and subcompact vehicles, as is the case in many Asian and other developing countries where mainly compact and subcompact cars are sold.

In this article, the components and operation of the current A/C systems with some details on the components as background information are first described. A brief history of the refrigerants and A/C system is then presented, followed by the developments of the major components of the A/C system. The SAE-initiated study is then summarized for an enhanced A/C system with R134a to reduce R134a emissions by 30% in the near future. Finally, the potential alternative refrigerant(s) selection and some historical attempts for alternate refrigerants (CO_2, R152a, and HC blends) are briefly summarized for reduction in global warming. While the auto A/C has become very sophisticated, the newer A/C systems are becoming more energy-efficient for desired high performance; the cost is continually reducing due to global competition with the same or better durability and reliability. Finally, some discussion is provided on ongoing efforts on A/C system heat load reduction and new developments in auto A/C systems.

BASIC OPERATION OF CURRENT AUTOMOTIVE A/C SYSTEMS

Two major types of A/C systems are used in the vehicles: TXV-RD and OT-AD. The components of a typical modern TXV-RD and OT-AD systems are shown in Figure 1a and b, respectively. In the TXV-RD system, the refrigerant flow rate is controlled by the thermostatic expansion valve (TXV or TEV) by monitoring refrigerant superheat at the evaporator outlet. The receiver-dryer (RD) is placed ahead of the TXV for separation of liquid and vapor refrigerant and storing access refrigerant required during cool-down and sudden increase in heat load. In the OT-AD system, similar functions are achieved by a fixed-diameter orifice tube (OT) placed ahead of the evaporator and an accumulator-dryer (AD) placed after the evaporator. Further details of components are provided later in this section. Moisture ingression in the refrigerant loop in the A/C system occurs through the porosity of hoses, less than perfect refrigerant line joints, etc. If this moisture is not removed, it can internally corrode the evaporator, TXV, and OT, and clog the "orifice" of the TXV. Hence, a desiccant bag is placed in the RD and AD bottles, whichever is used in the system selected.



(a)

(b)

Figure 1 Major types of automotive air-conditioning A/C systems used in vehicles: (a) TXV-RD, (b) OT-AD.

The basic operation of this system is now described starting with the compressor. The primary function of the compressor is twofold: (1) Compress and pressurize relatively cool gaseous refrigerant from the evaporator outlet (suction line) with minimum compressor power, and (2) deliver maximum amount of high-pressure high-temperature gaseous refrigerant to the condenser. These two objectives are measured/quantified by isentropic and volumetric efficiencies of the compressor, respectively. The compressor is powered by a drive belt from the engine, and its rotational speed (revolutions per minute, rpm) is generally higher than the engine rpm, and is decided by the chosen pulley ratio. The compressor has an electrically operated engagement clutch to turn the A/C system off or on. Next is the condenser in the refrigerant flow path; see Figure 1. The condenser is (and should be) located in front of the radiator. In automotive A/C systems, the condenser is typically a cross-flow heat exchanger in which air flows through the corrugated or flat louvered fins and the refrigerant flows through the flat multiport or round tubes (with or without microfins) in multiple passes in the direction perpendicular to the airflow. The condenser cools the high-pressure hot refrigerant gas coming from the compressor and converts it to liquid with generally a small pressure drop through the use of ambient air (relatively cool compared to the hot refrigerant) blown by the condenser/radiator fan. The exiting liquid refrigerant (subcooled in many cases) from the condenser is sent via a small tube (liquid line) to the RD (applies only to an expansion valve system). The RD is a metal can with a desiccant bag inside and allows only liquid refrigerant to go out. It is usually located near the condenser outlet pipe. Nowadays the RD bottle is an integral part of the condenser in modern high performance A/C systems, and such a condenser is referred to as an *integral receiver-dryer condenser* (IRDC). In this case, refrigerant passes through the RD before leaving the condenser through the condenser last pass as subcooled liquid. The objective is to improve the degree of subcooling of the refrigerant at the condenser outlet by allowing only already condensed liquid refrigerant. There is a negligible pressure and temperature change in the refrigerant through the RD, except that the moisture is removed by the desiccant.

Continuing the A/C system operation, as the high-pressure warm liquid exits the condenser and RD (Figure 1a) or condenser (Figure 1b), it passes through an expansion device (TXV or OT) which modulates the proper amount of the refrigerant flow rate going through the complete A/C system. Effectively, the TXV has a variable diameter orifice tube, and the OT has a fixed diameter orifice tube. Thus TXV allows more refrigerant flow rate at idle compared to that for the OT thus providing higher cooling at idle vehicle operating condition; ideally, both systems provide the same maximum design cooling performance at the city traffic conditions (40–50 km/h vehicle speed). For a given vehicle, the TXV-RD system has slightly better cooling performance than the OT-AD system. This is because the OT-AD system has higher pressure drop in the refrigerant line (the suction line) between the evaporator and compressor, since the AD bottle introduces additional pressure drop impacting the A/C system performance. At higher vehicle speeds, the TXV maintains desired refrigerant superheat at the exit of the evaporator by allowing more refrigerant flow rate through the system to meet higher cooling requirement. The OT cannot control the refrigerant exit condition at the evaporator outlet, but the bubble point (where the refrigerant starts vaporizing) moves within the OT from the entrance (high evaporator cooling condition) to the exit end of the tube within the OT (low evaporator cooling condition) to provide the required refrigerant flow rate to the evaporator and the A/C system. The pressurized liquid passes through the expansion device, with considerable reduction in the pressure and corresponding temperature.

The cold liquid/vapor refrigerant mixture from the expansion device is fed to the evaporator in an HVAC module located under the dashboard in the passenger compartment. It cools fresh or recirculated warm air, which flows into the car interior with the help of a blower to cool the passenger cabin. As the air is cooled flowing through the evaporator on one fluid side, the liquid/vapor mixture of the refrigerant is heated on the other fluid side and evaporates. The evaporated refrigerant gas then returns via the "large" suction line (tube and hose) to the compressor "suction" port to begin this whole process again in the TXV-RD system. In the OT-AD system, an accumulator-dryer is placed between the evaporator and compressor. It separates and stores any liquid refrigerant coming out of the evaporator before going to the compressor since there is no superheat control at the evaporator exit in the OT-AD system.

BRIEF HISTORY OF THE REFRIGERANT AND A/C SYSTEM

With the invention of R12 in 1928 by GM researchers came the dawn of automotive air-conditioning. The first prototype self-contained system was installed in a 1939 Cadillac. Packard Motor Company (later merged with Chrysler) in 1939 was the first company to offer a complete auto air-conditioning system for cooling in summer and heating in winter using R12 refrigerant. The first bus A/C prototype was developed in 1934 by a joint venture between Houde Engineering Corporation of Buffalo, NY, and Carrier Engineering Corporation of Newark, NJ, and others followed. Initial air conditioners had a number of problems, and the Second World War hampered the production/progress. By 1953, many of the problems had been resolved and General Motors and Chrysler came back with improved air-conditioning and that luxury became a necessity for a common car owner! In 1953, the Harrison Radiator Division of General Motors came up with a revolutionary air conditioner that was totally spaced in the underhood (compressor and condenser) and dashboard (HVAC module and expansion device), eliminating it from being in the trunk, which was the common practice until then for all car manufacturers. The use of desiccant material to absorb moisture in the refrigerant line started in 1953. Detailed early history of the refrigerant, components, and development/penetration of A/C system in vehicles is given by Bhatti [2–4]. The following are the milestones of the development of the A/C system after 1953 (Bhatti [3]):

- In 1955, GM developed the first A/C and heating unit that was front mounted, totally pre-assembled and pretested. By 1957, all car makers followed this design approach.
- To provide the evaporator freeze protection, a hot gas bypass valve was introduced in the A/C system in 1956.
- In 1957, air conditioning became a standard item in Cadillac Eldorado Broughams. The average price of all air conditioners sold in 1957 was $435.
- The popularity of auto A/C soared and the number of installed A/C systems on the vehicle tripled from 1961 to 1964. During 1963, Ford set the A/C unit price at $232.
- In August 1965, GM crossed the 5 million A/C unit production mark. GM also introduced first the Climate Control System on Cadillac. Industry-wide penetration of A/C reached 70% by 1980.
- Due to an oil embargo in 1973, an emphasis was placed on fuel economy. The Harrison Radiator Division of General Motors developed a cycling clutch orifice tube (CCOT) system replacing the Frigidaire valve-in-receiver (VIR) system, which resulted in the compressor off for one-third of the time rather than continuously running, thus improving fuel economy. By 1979, all GM vehicles used this CCOT system.
- In 1974, the world came to know about ozone depletion in the stratosphere due to R12 use. Note that the ozone layer blocks ultraviolet rays that would otherwise cause skin cancer for humans exposed to sun rays in sunbathing, common in Western countries. The Harrison Radiator Divison of GM analyzed nine refrigerants and by 1976 arrived at R134a as the replacement of R12, eliminating chlorine from the refrigerant. However, there was no commercial availability of R134a then; Allied Chemicals, the major company conducting

research on R134a then and located only 20 miles from Harrison, would supply about 1 lb of refrigerant per week and the need was about 1000 lb per week for A/C system development work at Harrison in those days. So the development work continued slowly. Although the viability of R134a was proven by Harrison through wind tunnel tests on the 1978 Chevrolet, and further development of A/C system was completed with R134a, no interest was shown by the worldwide auto industry till the Montreal Protocol was adopted by the United Nations in September 1987. The first major revolution in the A/C system thus came starting in the 1990s with the replacement of R12 by R134a to eliminate the ozone depletion in the stratosphere by introducing a refrigerant having chlorine replaced by fluorine in its composition. The commercial production of R134a started with DuPont and ICI in 1990.
- The changeover of R12 to R134a necessitated the following major changes in the A/C system: (1) a new condenser with about 20% higher condensing capacity to maintain the same operating system pressures so that a new compressor was not needed, (2) a change of the lubricant from mineral oil to compatible synthetic polyalkylene glycol (PAG) oil, (3) the expansion valve setting required a change for keeping cooling equivalent to R12 system, and (4) all rubber components required change from RBR to HNBR.
- Conversion from R12 to R134a in the United States, Europe, and Japan took place during 1991–1994. The rest of the world has changed to R134a as the refrigerant for the A/C system in new vehicles during late 1990s and early 2000s.

Global warming potential (GWP) was not an issue when changeover from R12 to R134a took place, although the global warming potential of R134a was significantly lower than R12, 1430 versus 7800; nature's own greenhouse gas, carbon dioxide, is the basis for the GWP yardstick, having a GWP of 1. According to the European Commission F-gas regulation, the refrigerant in the A/C systems for all new vehicle models from 2011 and all new vehicles manufactured from 2017 introduced in European Union (EU) must have a GWP of 150 or less. Several potential replacement refrigerants are considered and an account is provided in a later part of this article.

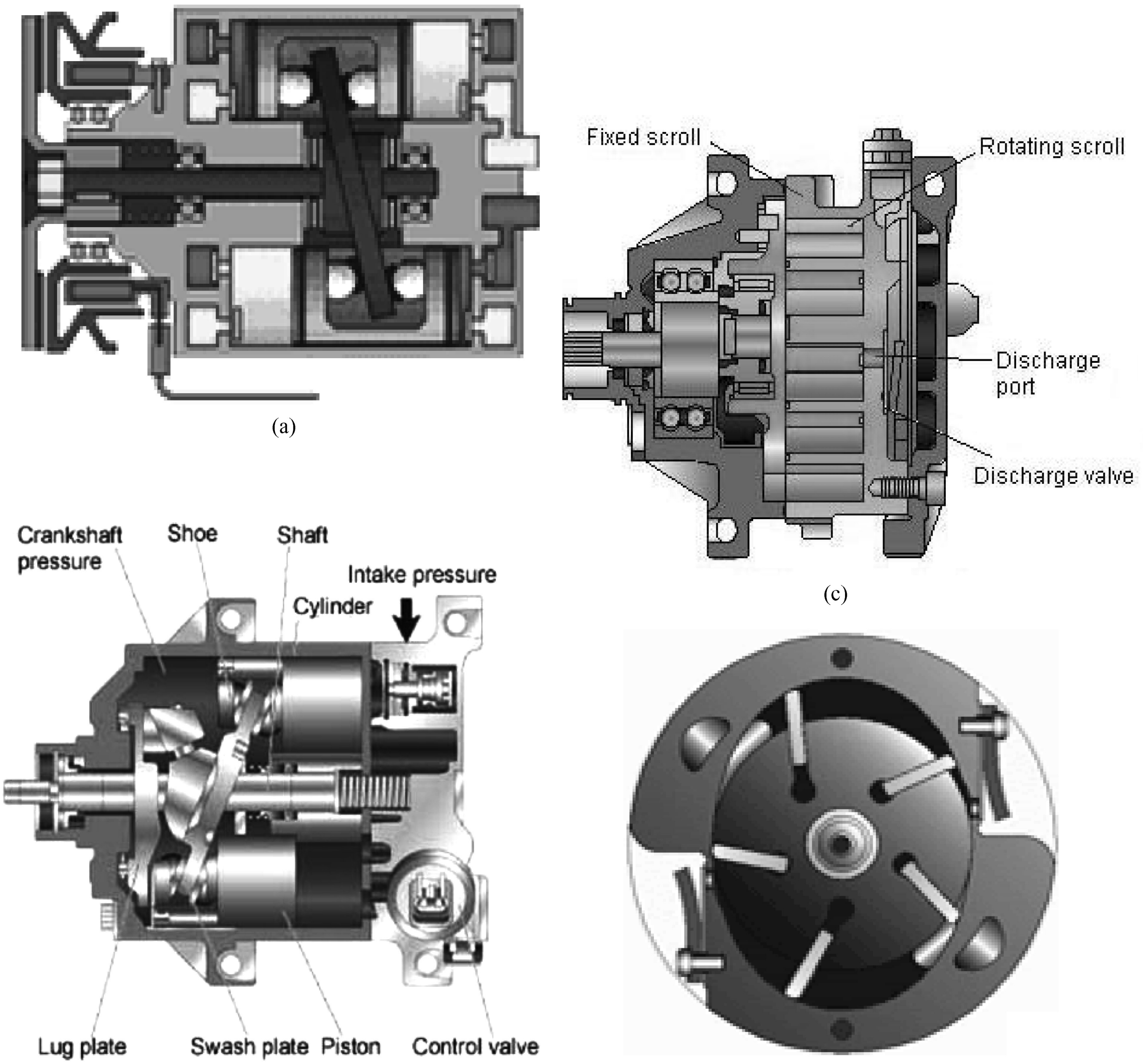
COMPONENTS OF THE A/C SYSTEM

Major components of an automotive A/C system are a compressor, a condenser, an expansion device, an evaporator, and a receiver-dryer or an accumulator-dryer, as described next with some historical development and/or current various designs in use. In addition, tubes and hoses are required to connect these components, and sensors for proper operation of the A/C system. With sensors becoming a very important part of the human comfort, they are also briefly described.

Compressors

The function of a compressor is twofold: to compress the refrigerant to the desired high pressure with minimum power requirement, and to deliver (circulate) the largest amount of refrigerant volume to the A/C system. These two functions are measured in terms of isentropic efficiency and volumetric efficiency, respectively. Major types of compressors used in the automotive A/C system are reciprocating compressors [fixed-displacement compressors (FDC), variable-displacement compressor (VDC)], and scroll and rotary compressors. These are shown in Figure 2. Fixed-displacement compressors were introduced with the beginning of the A/C development. In 1950s, the compressors weighed over 27 kg (60 lb). Today they weigh about 4–7 kg (9–15 lb). Along with the reduction in weight, the volumetric and isentropic efficiencies and durability/reliability have increased considerably and noise has reduced significantly. Reciprocating compressors have about 80% worldwide market share, and scroll and rotary compressors have about 20%. General characteristics of compressors are summarized in Table 1. In a fixed-displacement compressor (FDC), rotary motion of the shaft-swash plate assembly is converted into the reciprocating motion of the piston (fixed stroke length). Historically, first a single-acting piston compressor was introduced for the A/C application, and was further improved by modifying to a double-acting piston compressor for more power and better efficiency. The refrigerant flow rate is maintained by the pressure differential between the suction plenum and discharge plenum. In this compressor, the displacement (swept volume by the piston) does not vary with rpm. The refrigerant flow rate varies with the change in rpm only.

In a variable-displacement compressor (VDC), rotational motion of the swash plate is converted into reciprocating motion of a variable stroke length depending on the A/C cooling load. There is only one single-acting piston. This is because there is a mechanism on the other side (left-hand side in Figure 2b) for changing the inclination of the swash plate, which results in the variable stroke length of the piston. The mechanism consists of the lug plate (and springs) (shown in Figure 2b) plus the shaft-swash plate subassembly. A control valve is provided to sense the variation in heat load and change the displacement of the compressor accordingly. The VDC is more efficient at all operating conditions (from 5 to 95% compressor displacement) than the FDC in mild weather in spring/fall and summer, particularly in North America and Europe. With the change of swash plate angle, the compressor is operated with precise displacement at full stroke ($\approx$ 60–74% volumetric efficiency). Where the ambient conditions are very hot for most of the time in the year (e.g., in India, Mexico, etc.) and full compressor displacement is needed most of the time when the A/C is on, the FDC is primarily used due to its lower cost. The size of the VDC is approximately about the same as for the FDC for equivalent full stroke capacity, and hence the weight. VDC gives overall better performance in low/mild ambient conditions. Its performance



(a) (c) (b) (d)

Figure 2 Compressor types: (a) fixed-displacement compressor, (b) variable-displacement compressor, (c) scroll compressor, and (d) rotary compressor. Courtesy of Subros Ltd., New Delhi, India.

in hot ambient conditions is the same as that of the FDC of the same 100% full displacement. Its cost is about 20–40% higher than the equivalent full-performance FDC.

A scroll compressor is a rotary-type compressor, as shown in Figure 2c, where a moving scroll has an orbital motion around a fixed scroll. Motion of the scroll pulls in gas between the fixed and orbiting walls and continuously compresses it toward the center. This means there is no re-expansion of the compressed gas as in the FDC/VDC. Hence, the volumetric efficiency is very high, ~85–95%. Two types of scroll compressors are available, having fixed capacity and variable capacity. The advantages of the fixed scroll compressor over FDC are better performance at higher compressor speeds, higher volumetric efficiency, compact and low weight, and continuous compression process ensuring smoother gas flow. Disadvantages are that very high machining accuracy is essential, manufacturing of parts with complex geometry is difficult, an almost equivalent cost for the same cooling capacity and somewhat less durability, and lower performance at low rotational speeds, particularly at idle. A variable-capacity scroll compressor is more complex in design. Packaging is slightly larger, as would be expected, mainly for a control valve in the rear head ~15 mm longer. This compressor was used by GM in the past for minivans and some other luxury cars.

A rotary compressor, shown in Figure 2d, consists of a rotary piston with vanes inside a cylinder, which rotates eccentrically. This eccentric rotational motion is used to compress the refrigerant gas. It gives higher performance at lower compressor

Table 1 Important information for various compressors used in automotive air-conditioners

Compressor types	Compressor displacement, cc	Compressor power at 1800 rpm, kW	Cooling capacity at 1800 rpm, kW	η_i Range, %	η_v Range, %	Compressor weight, kg	Major advantages	Major disadvantages	Approximate worldwide business, %
Fixed-displacement compressors	80–200	1.48–3.6	2.94–7.2	45–70	50–69	4.3–7.2	Simple mechanism and reliable	Lower η_v and high noise due to frequent on–off	Approx. 66% decreasing
VDC, internally controlled†	120–170	~ 2.8	~ 6	45–70	60–74	~ 6.5	Better COP and human comfort	High cost and complex mechanism	Approx. 14% increasing
VDC, externally controlled†	120–170	2.2–2.8	4.9–6	45–75	60–74	5.3–5.4	Better COP and human comfort	High cost and complex mechanism	
Scroll compressors	60–115	1.71–	2.33–	60~80	85–95	4	Better η_v and compact in size	High cost, serviceability problem	Approx. 12% increasing
Rotary compressors	70–142	1.6–2.85	3–6.4	50~70	75–85	2.9–2.6	Low cost, compact in size and weight	Performance deteriorates at higher speeds and unsuitable for larger loads.	Approx. 8% increasing

†Variable-displacement compressors (VDC): continuous type internally variable, i.e., mechanical control, continuous type externally variable, i.e., electro-mechanical control.

speeds. It has a smaller number of parts. Hence, its cost is low. Major advantages are the simple mechanism, lower number of parts, cheapest, easy to manufacture, and better performance at vehicle idle conditions. The major disadvantages are that it is only applicable for lower cooling requirement (small cars), and compressor performance deteriorates at higher speeds. Because of the construction features, rotary and scroll compressors can tolerate some liquid better because the liquid refrigerant can escape from the compressor inlet to outlet without damaging internal parts.

The compressor requires lubrication. Because of the construction features, it is not easy to separate and return the lubricant from the refrigerant at compressor outlet to compressor inlet (this development though is continuing). As a result, the lubricant circulates through the complete refrigerant circuit. In a properly designed system, refrigerant brings the right amount of lubricant to the compressor for lubrication. Mineral oil has been used with R12 refrigerant. Since it does not mix with R134a, a special synthetic lubricant such as PAG (polyalkylene glycol) or POE (polyol ester) is used with R134a. Note that POE oil is compatible with both R134a and R12 refrigerants, as well as with the residual mineral oil that may still be in the A/C system. It is often used when retrofitting an older R12 A/C system to R134a.

Condensers

In a condenser, refrigerant flows on the (flat or round) tube side, and the ambient air from the vehicle front grill flows on the fin side. The refrigerant is de-superheated, condensed, and subcooled in the condenser with cooler ambient air flowing on the fin side. The refrigerant rejects heat in the condenser, which is gained in the A/C system as follows: heat transfer in the evaporator from air to refrigerant (60–65%), compressor power input (30–35%), and heat gain (3–5%) in the refrigerant lines in the engine compartment.

The following historical developments of condensers are summarized from Ravikumar et al. [5], and typical condenser development is shown in Figure 3. The mass production of the A/C system started with the 1954 Pontiac at the Harrison Radiator Division of General Motors Corporation, now Delphi Thermal and Interior System of Delphi Corporation. After trying out different designs during 1954–1956, production of condensers with round tube and flat fin design started with wavy fins in 1956; in early 1980s, the louver fins replaced the wavy fins. In tube-and-fin condensers, tubes are mechanically expanded onto the fins, thus not requiring brazing and associated cost. However, the performance is also lower compared to serpentine (thin flat multiport tubes) and parallel flow (also referred to as multiflow or headered tube-and-center) condensers. The first-generation serpentine condensers were sold by Modine in 1957. Serpentine tube and corrugated louver fin condensers were introduced during the late 1970s through 1980s. Their heat transfer performance is higher than that for mechanically expanded round/oval tube-and-fin condensers for equivalent air-side pressure drop.

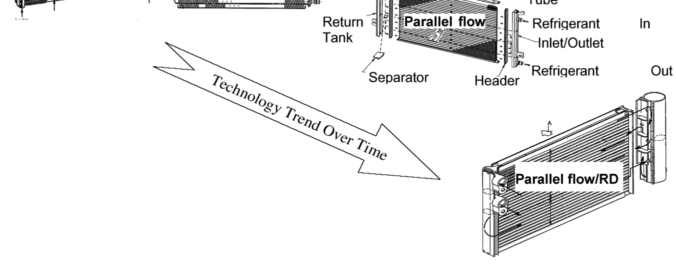


Figure 3 Historical condenser developments, from Ravikumar et al. [5].

The parallel flow condenser was introduced in the late 1980s due to its higher performance (not achievable in a serpentine condenser for the same packaging envelope), required with the change of refrigerant from R12 to R134a. This condenser has extruded microchannel (flat) tubes and corrugated multilouver fins.

Depending on the amount of the heat rejection required from the condenser, a number of different condenser designs are used worldwide today:

1. For lower cooling requirements, mechanically expanded round/oval tube and louvered/wavy flat fins are most economical since this design does not require brazing. Since the 1990s, microfins are being used in round tubes of round tube and flat louver fin condenser design; such designs have two tube rows; microfins increase heat transfer surface area and hence the performance. On the air side, improvements have been made in the design of multilouvers, and this fin design is still mostly used. These condenser designs have two tube rows, fin density 400–800 fins/m, fin thickness 0.075–0.125 mm, core depth 25–44 mm, and tube diameter 6–7 mm. Both multilouver and wavy fin designs are being used.
2. For medium cooling requirements, condensers with brazed serpentine multiport tubes and corrugated multilouver fins are also used; such a condenser has only one serpentine circuit for refrigerant flow and those with higher cooling requirement have two parallel serpentine circuits. Current designs have fin density 400–800 fins/m, fin thickness 0.075–0.125 mm, fin height 10–15 mm, core depth 25–38 mm, and tube height 3–5 mm.
3. For even higher cooling requirements, brazed parallel flow condensers are used. This condenser has radiator-type construction with tanks on both sides of the condenser and refrigerant having multipass flow, with the number of tubes reducing in succeeding passes due to reduction in refrigerant volume as it is condensing. Most such condensers have extruded multiport tubes on the refrigerant side, but alternative designs with folded tubes with internal fins have also been used. Current designs have narrow height tubes (0.9 to 1.2 mm), thinner fins (0.075–0.1 mm), fin heights 5–9 mm, and core depth 16–25 mm.

Usually the cooling performance of the mechanically expanded (e.g., tube and fin) condenser is low (about 2–4 kW) versus the brazed condenser's (serpentine and parallel flow) performance of 3–10 kW or so. Thus there is some good overlap of the performance, and the eventual decision in selection is primarily based on the cost.

In the conventional automotive TXV-RD air-conditioning system, an RD and a condenser are separately mounted in the engine compartment. This design requires more packaging space in the engine compartment and adds cost to the air-conditioning system. In one of the latest developments in design of the condenser, the RD bottle is integrated with one of the condenser tanks, thus reducing the space requirement and cost. This design eliminates separate mounting space for the RD bottle, one or two brackets for receiver mounting, pipe connectors to connect the condenser and receiver, the larger quantity of the refrigerant contained in the liquid line, and additional manufacturing operations at the car assembly line. Integrating the RD in the condenser by connecting it before the last pass of the refrigerant circuit allows the liquid coming out of the RD to be further subcooled in the last pass of the condenser, thus producing more subcooling (5–7°C) in the condenser and resulting in higher A/C system performance with about 5–10% higher operating pressures on the refrigerant side. Also, now only one part (IRDC) is manufactured, thus reducing the manufacturing cost and the space requirement associated with the RD and piping) in the engine compartment, as mentioned earlier.

Evaporators

The function of the evaporator is to dehumidify and cool the ambient air going to the passenger compartment, thus reducing the sensible and latent heat from the incoming air to the evaporator. The evaporator is located in the HVAC module before the heater core, and the heater core is positioned at some angle with respect to the evaporator in most designs. Equal or lower amounts of airflow (than that going through the evaporator) can go through the heater so that bilevel performance (hot air to the feet and cold air to the face) from the A/C system can be achieved when desired. HVAC module design allows conditioned air to the passenger cabin in the following modes: cooling (face), heating (foot), bilevel (foot/face), heating/defrost (foot/defrost) mode, and defrost/demist. Depending on the design requirements, either fresh or recirculated air is used in some or all of these modes.

The following is the summary of early developments of the evaporator at the Harrison Radiator Division of General Motors in the United States. Between 1954 and 1960, several design changes were introduced for evaporators. Since 1960 through about 1980, the evaporator had a ribbed plate refrigerant tube and corrugated split bump louver fin design. Only salt-dip brazing technology was used for brazing since vacuum brazing and neutral environment brazing processes were not available. Because of the required drainage of the salt in the core after the salt-dip brazing process, all early designs were single-pass evaporators, and, as a result, required more heat transfer surface area and hence the core depth. There was also considerable air-side temperature maldistribution downstream of the core due to the single-pass cross-flow design. Tube-and-fin evaporator design was also available, and it did not require any brazing. However, the performance was quite poor compared to the brazed construction, and the cores were deep (typically 100 mm). This core construction has been largely replaced by the plate-fin multipass brazed evaporators.

Since the introduction of vacuum brazing technology in early 1980s, it has been used for brazing evaporators, which allowed multipassing on the refrigerant side and reduced environmental pollution compared to the salt-dip brazing process. The vacuum brazing technology was replaced by controlled atmosphere brazing (in nitrogen environment) in 1990s by some manufacturers because the latter does not require vacuum and is more forgiving to contaminants on the fin surface, and is less costly. Two or more passes on the refrigerant side have become common now, allowing higher performance and reasonably uniform air temperature distribution downstream of the evaporator for the same packaging. The cup design (which forms refrigerant distribution headers) of the refrigerant tube plates changed from round cups to rectangular cups for improved packaging in 1980s and also for more heat transfer surface area for given overall outside width of the refrigerant tubes. Also, multilouver fins replaced the split-bump fins to reduce air-side pressure drop at the same heat transfer later in 1980s. However, this fin geometry retained more water in the core after air-conditioning being shut off. As a result, it had created an odor problem in the evaporators in earlier designs in late 1980s. To minimize the condensate retention in the core, the U-channel single-tank vertical tube plate design was introduced. This design provided better condensate drainage than horizontal two-tank tube plate designs, but resulted in a larger refrigerant-side pressure drop and slightly lower performance than the two-tank design. Both single-tank and two-tank brazed evaporators are now common in the industry. From 1980 to the present, the core depths have been reduced to about 40 mm and below, fin thickness 0.075–0.1 mm, fin heights 7–11 mm, and no significant change in the fin density (480–560 fins/m) due to condensate retention and subsequent bridging of the louvers in the fins with condensate associated with higher fin density (lower fin pitches).

Since the 1980s, similar to serpentine tube and corrugated fin condensers, serpentine tube and corrugated fin evaporator design surfaced mainly in Asia that could use the same or similar tooling for manufacturing. However, the performance is relatively low due to no cross-mixing of refrigerant at a given cross section along the flow path due to flat multiport tubes; once the refrigerant evaporates in the front flow passages of the multiport tubes in the airflow path, the vapor flows through these ports, and it results in excessive refrigerant side pressure drop without contributing to heat transfer. The serpentine evaporators are still used in applications requiring low cooling (e.g., for compact and subcompact cars) due to their lower cost and their flexibility in size/shape compared to the plate type design. The evaporator development by Denso is presented in Figure 4 (Reddy et al. [6]).

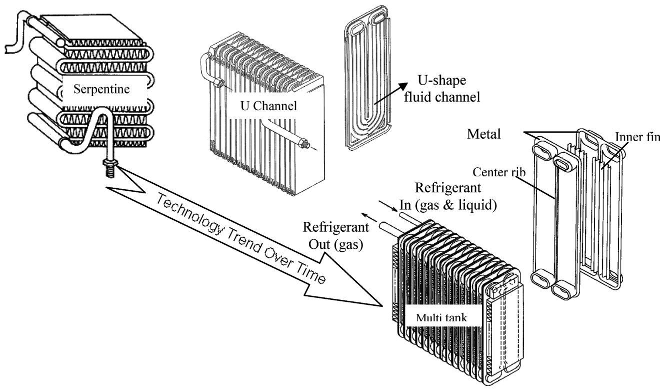
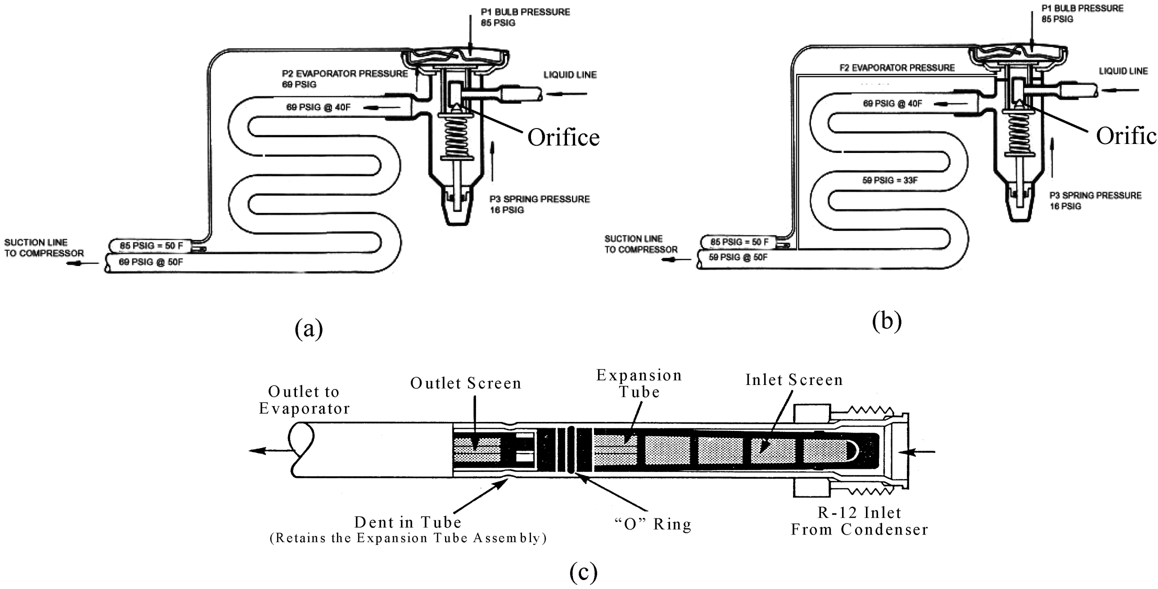


Figure 4 Historical developments of Denso auto A/C evaporators, from Reddy et al. [6].

Expansion Devices

Two most common devices used in the A/C system for refrigerant expansion are the thermostatic expansion valve and orifice tube, as shown in Figure 5. They are described next.



(a)

(b)

(c)

Figure 5 Common devices used in the A/C system for refrigerant expansion: (a) internally controlled thermostatic expansion valve, (b) externally controlled thermostatic expansion valve, and (c) an orifice tube.

Thermostatic Expansion Valve (TXV)

The thermostatic expansion valve, as shown in Figure 5a and b, is used in the A/C system due to resulting in higher performance in the A/C system, particularly at idle, but it costs more than the OT. The TXV has effectively a variable-diameter orifice and provides optimum/maximum cooling at idle in addition to the city traffic operating condition; the OT is designed to provide optimum/maximum cooling primarily at the city traffic condition. Generally, there is more than sufficient cooling available at the highway speeds so the choice of TXV versus OT is generally not for cooling performance consideration at those vehicle speeds. The TXV regulates refrigerant flow rate into the evaporator to control evaporator outlet superheat, typically preset at 3–5°C. Briefly, the TXV operates as follows. Capillary tube/bulb of TXV senses the evaporator pipe temperature at the outlet, which reflects the evaporator outlet superheat. The temperature sensed is converted into pressure of the refrigerant in the capillary tube. This pressure is sensed on one side of the diaphragm of the TXV and the other side senses the pressure due to the spring force of the TXV and refrigerant outlet or inlet pressure, depending on the externally or internally controlled valve (Figure 5a or b). This pressure balance locates the position of the valve and hence the opening for refrigerant flow rate through the TXV to the evaporator. Many variations of TXVs have been evolved in the recent past to control the refrigerant flow rate through the evaporator, and the details are beyond the scope of this article. A TXV can be made to restrict flow to the evaporator when the suction pressure approaches a preset upper limit (for durability of the TXV with liquid-charged system or to favor the front system in a front/rear system at idle). This characteristic is referred to as maximum operating pressure or MOP. In a dual (front and rear) A/C system, TXV is always used with a rear evaporator even with the OT-AD system since there is no second AD provided in the system to separate any liquid before it goes to the compressor.

TXV capacity and superheat selection are very important to ensure a good design and no problems in the field operation. Usually, the TXV capacity is selected as 0.5 to 1 times the evaporator design cooling load; e.g., 0.8 ton to 1.2 ton TXV is used with the A/C system requiring about 1.2 to 2 ton cooling in the evaporator. The following are the general operation/design considerations for TXV.

- If the TXV capacity is the right amount with the right size components (compressor, condenser, and evaporator) in the A/C system, the TXV should provide good cooling at all operating conditions including long idle running. If the system is not designed properly, it will not give designed cooling performance and will shut off the A/C system due to high head pressure only at idle after running for some long period.
- If the TXV capacity is too small, the system will have less refrigerant flow rate going through TXV and will result in poor performance (because evaporator load/capacity will be low). Therefore, condensing will be excellent and head pressure will be low. At loads higher than the TXV capacity, high superheat will result and cooling will not be adequate. Too small capacity of TXV will increase the head pressure and the pressure switch will cut off the compressor if the head pressure exceeds its set limit.
- If the TXV capacity is too big compared to the right amount (i.e., large TXV), it will provide good cooling at high loads; but at low cooling loads, the TXV will start hunting (cycling—cuts off and cuts in too frequently) as it tries to maintain the required degree of superheat at the evaporator outlet. This can cause a noticeable noise in the car cabin, and can even result in TXV durability considerations. The cycling will be more noticeable at high vehicle speed such as 100 km/h in low ambient temperatures such as during late evening or early morning of a sunny day.
- TXV capacity should be large enough to prevent excessive throttling and excessive superheat at high load and should be small enough to prevent loss of control (excessive opening and closing) at low load due to core freezing.
- If the ambient temperature is low, there is not enough cooling load on the system. The refrigerant temperature will go down continually, and the "right size" TXV in a moderate to high ambient condition is too large for such low ambient operating condition, so the core will start freezing. The thermistor in such a case will shut off the A/C system (when the air outlet temperature at the coldest point in the outlet face of the evaporator reaches 1°C, let us say) and re-engage the clutch (the system is turned on) when that temperature reaches 4°C for example. Actually, the clutch cut-off/cut-in temperatures are determined empirically and the value will be different depending on the distance of the thermistor away from the evaporator outlet face (somewhere between 5 and 10 mm).
- In the TXV-RD system, the TXV controls the refrigerant superheat at the evaporator outlet. The selection of this superheat is also important. If the refrigerant superheat is selected too low, the evaporator will be flooded (since flow and heat transfer is not uniform in any/last evaporator pass) and the liquid coming out will lose the chance to further cool the air. If the refrigerant superheat is selected too high, the evaporator will have single-phase heat transfer in the last portion of the evaporator and that surface area is wasted due to negligible heat transfer. Also, it results in high compressor inlet temperature and therefore high discharge temperature. This may cause oil overheating and compressor durability problems. Due to nonuniform heat transfer in individual tubes of the evaporator because of a number of reasons, usually the TXV is adjusted to ensure very minimum amount of liquid coming out of the evaporator to ensure good performance and no liquid reaching the compressor in any ambient conditions. Hence, some minimum superheat, such as 1–2°C, is set for refrigerant at the evaporator outlet.

Orifice Tube (OT)

The OT (Figure 5c) also "controls" like TXV or allows the refrigerant flow rate through it, but based on a different principle, as explained next by the bulleted items. The refrigerant enters the OT in the liquid phase and it will start vaporizing in the OT depending on the system operating point. In this A/C system, the excess liquid refrigerant (not circulating in the A/C system) is stored in the accumulator located downstream of the evaporator. In contrast, it is stored in the RD located upstream of the TXV in the TXV-RD system. Now let us describe the OT operation.

- When refrigerant flows through an orifice tube, it generates less pressure drop if it is a liquid and more pressure drop if it is a gas. For a given pressure drop, the flow will be high if the bubble point (where the liquid refrigerant starts boiling/vaporizing) is near the exit of the tube since the refrigerant will be liquid for most of the tube's length and it will be gas only for a short length.
- Conversely, for a given pressure drop, the flow will be low if the bubble point is at the beginning of the tube since the refrigerant flows mostly as a gas (having high pressure drop) and as a liquid only for a short length.
- Now let us explain the transient operation of the OT-AD A/C system. Consider a system operating at low load (say a low blower speed) and suddenly switched to a high blower speed. At low load, the evaporator and accumulator store a lot of liquid. Because there is a lot of liquid in these components, there is not much liquid in the condenser. Since the liquid level in the condenser is low, the subcooling will also be low. Therefore, when the refrigerant gets to the orifice tube with low subcooling, it vaporizes near the entrance to the tube. Since the tube contains mostly gas, the pressure drop is high and the flow rate is low. Remember that low subcooling means the refrigerant is near the saturation pressure, so only a small drop in the pressure is needed to achieve saturation. So now look at what happens when the blower speed is increased to high. The heat transfer increases and the liquid boils out of the evaporator and accumulator since the refrigerant flow rate cannot increase immediately. The liquid from these components is transferred to the condenser and increases the level of liquid in the condenser. This increase in liquid level means that the liquid subcooling increases. When this increased subcooled liquid gets to the orifice tube, it travels farther down the tube before the pressure gets to saturation. This results in reduced pressure drop through the tube and the flow increases until the system balances itself again.
- Now consider the steady-state A/C system operating points with increasing cooling loads. The corresponding liquid refrigerant flow rates through the A/C system are increased. This translates into the bubble-point location moving from the OT inlet toward the OT outlet, with more liquid flowing through the OT. In a properly charged system, at the highest cooling load steady-state operating point, the bubble point is kept within the OT near the outlet by design so that there is control in the operation.
- At a steady-state operating point of low cooling loads, in a system not properly designed, with low AD bottle volume, the excess liquid in the AD bottle can get out and go to the compressor causing poor performance due to excessive refrigerant flow rate. Excessive liquid flow drives up the suction pressure. Hence, this design point should be evaluated up front for the proper size of the AD bottle.
- During the real operating conditions (which can be transient), the OT controls exactly the right amount of refrigerant by describing the process that takes place when load changes to rebalance the system. This is based on the fact that there is a fixed amount of liquid refrigerant in the system; if most of the liquid is in the condenser, the subcooling into the OT will be high and the bubble point will be near the exit. Conversely, if most of the liquid is in the evaporator and AD, there will not be much liquid in the condenser; hence the subcooling into the OT will be low and the bubble point will be near the entrance.
- If the system refrigerant charge is too low or the system A/C load is too high compared to the right design, the refrigerant coming out of the OT may not have any liquid and its temperature may be too high at its exit to provide proper cooling in the passenger cabin at any operating point.

Many Tier 1 suppliers from the United States and other countries provide the OT-AD system for vehicle operation in moderate climate conditions (such as in North America, northern Europe, etc.); they use only one OT size (diameter and length) for the A/C systems of the complete range of their cars to sport utility vehicles (SUVs).

Receiver-Dryer and Accumulator-Dryer

The receiver-dryer (RD) is used with the TXV system and accumulator-dryer (AD) is used with the OT system. The RD is located upstream of the TXV, and the AD is located downstream of the evaporator. The specific functions of the RD are threefold: (1) to separate the incoming refrigerant from the condenser into liquid and vapor, and allow only liquid to exit, which enters the TXV; (2) to store excess liquid refrigerant to meet the high A/C demand at initial cool-down of the hot vehicle and also to meet high cooling loads; and (3) to remove moisture and filter out debris from the circulating refrigerant. Similarly, the specific functions of the AD are threefold: (1) to separate the incoming refrigerant from the evaporator outlet into liquid and vapor, and allow only vapor to exit, which enters the compressor, with (2) and (3) the same as those for the RD. The AD should be located at a higher position in the engine cabin than the compressor so that the liquid does not enter the compressor after overnight parking of the vehicle (i.e., vapor refrigerant is condensed, if any). In both RD and AD, a desiccant bag is placed. It serves a vital function of removing the moisture ingression from the pipe joints and hoses, since the water and refrigerant form corrosive acids that can internally corrode the system, in addition to reducing the performance.

Sensors

With the advancement of technology, the use of sensors is increasing rapidly in the automobile. Some of the major sensors used for the operation and control of the A/C system in vehicles are pressure, temperature, blower speed, solar insulation, cabin interior comfort condition in hot and cold climates, etc., as follows:

- The pressure sensor, a replacement for the pressure switch, gives electrical reference voltage corresponding to the pressure applied. An ECU (electronic control unit) controls the compressor on/off, and condenser and radiator fan speeds based on the reference voltage supplied by the pressure sensor.
- Infrared sensors sense heat from the passengers and send the signal to A/C controls for human comfort.
- Fully automatic temperature control (FATC) is increasingly becoming a common feature for passenger comfort, with the following features being considered currently: automatic control of the temperature in single versus multiple zones in the passenger cabin; automatic control of blower speed (airflow), recirculation/fresh air mode; automatic cutoff/on of the A/C compressor to maintain the set cabin temperature; A/C cutoff in the vehicle open door condition; PTC heating in cold climate; improvement in thermal comfort by using neural network; close control on humidity, bacteria, dust, pollen, etc. More functions are being added as more features are put in such as seat warmer/cooler, spot cooling, etc.

ENHANCED MAC SYSTEM

The Improved Mobile Air Conditioning Cooperative (IMAC) 2-year research program was announced by the SAE (Society of Automotive Engineers) on April 22, 2004, and commenced in December 2004 to address all aspects of lifetime vehicle air-conditioner environmental performance using HFC-134a refrigerant. Participants included international automobile and air-conditioner system manufacturers, component and equipment suppliers, refrigerant manufacturers, MAC service providers, and the U.S. Environmental Protection Agency. This project was funded with more than $1.7 million in cash and approximately $2.0 million in in-kind industry contributions (28 corporate sponsors). Four teams were formed. A summary is provided next, condensed from the outcome of this study reported by Sciance [7].

Four teams were formed to study and recommend various aspects affecting design, operation, maintenance, and disposal of the MAC system.

- The goal of Team 1 was to reduce the refrigerant leak by 50%. Baseline annual leakage rates of 8–18 g/yr were lower than the specs by European Commission (40 g/yr for a single A/C and 60 g/yr for a dual A/C) so there is no need for further improvements. The conclusion of Team 1 was: The baseline leakage rates are low for typical vehicles with moderate J2727 scores of 2.3–2.6 (J2727 is a spreadsheet developed to rate each air-conditioning system).
- The goal of Team 2 was to improve system efficiency 30% on four demonstration vehicles: Dodge Caravan (dual system), Ford F150, Toyota Camry, and Pontiac Grand Prix. The suggestions included improvement in piston compressors and alternative technologies; improvements in evaporator and condenser effectiveness; optimized superheat, subcooling, and compressor controls; and optimized plumbing and control of recirculation. Results showed potential for 20–30% improved coefficient of performance (COP) at low loads with increased subcooling in the condenser, 20% improved COP at low loads with evaporator superheat control study, and 15% improved COP with improved efficiency compressors.
- The goal of Team 3 was to reduce vehicle cooling load by 30%. Recommendations were made for power ventilation, solar reflective glazing, solar reflective paint, lightweight insulation, shades, and ventilated seats.
- The goal of Team 4 was refrigerant containment during service. The SAE J1627 standard was developed for leak detection at 4 g per joint per year (current standard 14 g per joint per year) with a probe distance 3/8 inch (now 1/4 inch). SAE J2210 standard was developed for equipment and recovery, recycling, and recharging procedures. Many of the standards in SAE J2210 have been updated by J2788, which took effect on January 1, 2008. The tests showed that the old procedures left as much as one-third of the refrigerant in the system, from which it probably leaked when repair procedures began. So the new procedures should be far better. Reducing refrigerant left in system at recovery could reduce emissions by millions of pounds per kilogram at service annually.

To reduce the leakage at flexible coupled hose assemblies in field, a recommendation was made to conduct laboratory testing to evaluate and to develop a cost-effective means of field-coupled assemblies for leakage. The SAE Service Technology Group is charged to develop an analytical tool to evaluate service procedures to focus on leak detection and diagnosis, and to also collect data and perform refrigerant mass balance to identify and quantify the sources of all lifetime R134a emissions. Better compliance and improved recovery techniques are needed to reduce emissions by 7 to 10 g/yr.

OEMs and Tier 1 suppliers are trying to develop partnership with the Automotive Recyclers Association, raising awareness and developing strategies to improve refrigerant recovery and better compliance during service, vehicle end of life (EOL), and from the use of small 340 g R134a refrigerant cans and 13.6-kg cylinders. Emissions from these sources are somewhere between 13.1 and 42.6 gm-/yr refrigerant per operational A/C fleet in the United States. Considerable impact will be realized if this heel is eliminated or minimized.

The procedures, system control strategies, and vehicle hardware demonstrated in this IMAC program have influenced vehicle design and become the benchmark for new R134a systems.

ALTERNATIVE REFRIGERANTS

As mentioned earlier, R134a has a significant global warming potential. F-gas final regulation by the European Commission to phase out R134a from mobile A/C during 2011–2017 states: Replacing MAC refrigerant must have global warming potential (GWP) less than 150; there is refrigerant leak rate restriction for F-gases starting in 2008 and strict inspection and repair regulations for others. R134a leakage rate should be within 40 and 60 g per year, respectively, for single and dual evaporator systems, effective in June 2009 for new "type" vehicles and in June 2010 for all new vehicles in Europe. Reduce emission of greenhouse gases by 8% compared to 1990 levels during 2008 to 2012. The refrigerant in the A/C systems for all new vehicle models from 2011 onward, and all carryover models from 2017 introduced in the EU must have a GWP of 150 or less. In the United States, the California Air Resources Board Climate Action Team proposed regulation to phase out R134a from heavy equipment starting 2010 and from cars starting 2017. There is also a general global consensus that there will be one alternative refrigerant globally. The desired characteristics for a new refrigerant must meet the following four criteria (Minor [8]):

1. Environmental: zero ozone depletion, global warming potential index less than 150, and Life Cycle Climate Performance (LCCP) low (measured in terms of annual kg CO_2 equivalent emissions); it is currently between 150 to about 500 kg annual CO_2 equivalent total emissions (direct and indirect) based on major cities/countries in the United States, Europe, and Japan (Hill [9]). At present, there is no regulation imposed on LCCP.
2. Performance: It must have all the required/desired performance characteristics in a vehicle, such as desired performance in all vehicle operating conditions and in all climates, compatible with the existing A/C systems (a desired characteristic), must be energy efficient, must have proper lubricant, and it must be compatible with the materials and thermally stable. Improved R134a system should have the refrigerant leakage rate reduced to less than 40 g per year; recent studies show that the leak rate of most new vehicles is less than 20 g/yr. Worldwide search has resulted in the following new refrigerants as potential refrigerants for the replacement of R134a: R1234yf, CO_2, R152a, Honeywell Fluid H, DuPont DP1, and INEOS Fluor AC1. GWP values of these alternate refrigerants are presented in Table 2. All of them have zero ozone depletion potential. A brief description of these refrigerants is provided in the next two sections based on the presentations at the VDA Winter Meeting in 2007 and the SAE summer meeting in 2007.
3. Safety: It must pass through the safety regulation of regulatory agencies: Toxicity tests and the flammability index must be less than 2. ASHRAE Standard 34 classifies toxicity (tox) and flammability, where tox is labeled A for low tox, B for moderate tox, and C highly toxic, and the numbers are 1 for nonflammable, 2 for moderately flammable, and 3 for highly flammable. For example, R134a is an ASHRAE A1, propane is an A3, and R152a is an A2. ASHRAE Standard 34 is often used as a metric in defining safety requirements for various applications, but the mobile A/C industry would require a much more definitive tox assessment and criteria prior to use. For alternative refrigerants, there is no requirement imposed that it should be nonflammable, but if the refrigerant is nonflammable, it is preferred.
4. Viability: It must meet the European Commission F-gas directive. Raw material should be available and manufacturable. Cost-effective transition should be for the entire value chain, and must be a global industry solution.

Table 2 Important properties of alternate refrigerants

	R134a	R1234yf	CO_2	R152a	Fluid H	Fluid DP1	Fluid AC1
GWP	1430	4	1	124	<10	≈ 40	<150
Flammability	1	2	1	2	1	1	1
Toxicity	A1	A1	A1	A2	A3	tbd	tbd

With the preceding criteria in consideration, several alternative refrigerants have been evaluated over last few years: R1234yf by DuPont and Honeywell, carbon dioxide by German companies (VDA [10]), Delphi R152a, Honeywell Fluid H, DuPont DP1, and INEOS Fluor AC1. Honeywell Fluid H was found to be toxic in 2007. DuPont DP1 may have some toxicity concern. DuPont and Honeywell then jointly came up with R1234yf, which is the most likely candidate today for a direct replacement of R134a. The German VDA (Verband der Automobilindustrie) Association (VDA [10]) has officially announced that it intends to use CO_2 as an alternate refrigerant.

Proposed Alternate Refrigerants

Several alternative refrigerants have been evaluated over the last few years. They are R1234yf, CO_2, R152a, DuPont DP1, Honeywell Fluid H, and INEOS Fluor AC1. At the time of the publication of this article, two refrigerants are still being considered to replace R134a, as described next.

R1234yf

After Honeywell Fluid H was found to be toxic, DuPont and Honeywell worked together developing a pure refrigerant, an unsaturated fluorinated hydrocarbon, 2,2,2,3-tetrafluoropropene, or a hydrofluoroolefin, HFO-1234yf (which was the major component of Fluid H). This refrigerant appears to be the best drop-in refrigerant replacing R134a. It was not considered earlier because it is mildly flammable (but significantly less than R152a and R32). A CFD study (Nielsen et al. [11])

showed that it has a significantly smaller envelope and small volume than R152a from flammability viewpoint. Since this refrigerant–air mixture does not pool in other regions of the car during the leak, it reduces the possibility of an ignition source. It is considered flammable according to the ASME test and is classified as such by ASHRAE. Testing indicated that flows of the fluid from simulated leaks (pinhole as well as pipe burst) seemed to be impossible to ignite with likely ignition sources available in a car, such as red hot surfaces or sparks. Although a video was shown of burning R1234yf, the conclusion seemed to be that the presence of oil was required (under which condition an R134a leak would burn also). The JAPA-JAMIA Consortium (Ikegami et al. [12]) has evaluated this refrigerant thoroughly and found no concerns whatsoever from a viability point of view as a simply drop-in refrigerant that can be implemented at any time without any further development work.

The other properties of R1234yf are as follows: The ODP is zero since it does not have any chlorine. The 100 year global warming potential is 4, very negligible for making any significant contribution to climate change. Atmospheric lifetime (before it disintegrates) is 11 days, compared to 12 years for R134a. This refrigerant has a slightly higher molecular weight than R134a (114 vs. 102); hence, it will require correspondingly more charge. This refrigerant offers equivalent or lower toxicity compared to R-134a or R-12 in terms of both human health effects and ecological effects. Pull-down performance is equivalent to slightly better, and high-side pressure is the same to 5% higher, compared to R134a. The cooling capacity is within 95% of R134a for most vehicles and in most operating conditions (Ikegami et al. [12]).

CO_2 (Carbon Dioxide) System

The use of carbon dioxide as a refrigerant started for ice making in 1847, and by 1930 it replaced many alternative fluids for refrigeration and became the most common refrigerant. With the discovery of R12 in 1928 by GM researchers and subsequent other refrigerants, CO_2 was again replaced by 1940s by R12, R22, etc. for refrigeration and air-conditioning, and now again it is being considered as a "new" refrigerant.

The advantages of CO_2 as a refrigerant are as follows: GWP = 1, non-HFC/natural fluid, nonflammable, eliminates the need to recycle, good heat pump performance (heat pump technology not yet developed for vehicles, which would eliminate the heater in the vehicle), and low refrigerant cost. While its global warming potential is 1 (all fluids are measured on this baseline index), the effective global warming potential of CO_2 is higher than that for R134a due to the following reasons: The A/C system works in transcritical region of the fluid at very high operating pressures (about 6–8 times higher than that for R134a). This would result in slightly heavy A/C system components compared to those for R134a, resulting in a fuel penalty in carrying the extra weight. The equivalent global warming potential of CO_2 system is slightly higher than that of the current R134a system. Other disadvantages of the CO_2 system are as follows: high system cost due to new designs required for all system and components, high tooling/production costs, additional components needed, safety system needed (as mentioned at the end of this paragraph), increased system weight, full efficiency potential needs to be demonstrated, system leakage and leak detection methods are very serious problems due to extremely small molecule size of CO_2, and training of personnel. Note that CO_2 is not toxic in the classic sense, but its effect on breathing and the central nervous system can cause safety issues and possibly death under right conditions. It may create disorientation while driving. The prevailing belief is that a warning system is needed to detect the CO_2 leakage in the passenger cabin.

The German VDA will continue to work on CO_2 as an alternate refrigerant.If there are any problems found, the decision may come at any time in future before January 2011 deadline. The final solution in Europe is wide open still but R1234yf appears to be the most promising at this stage. All the other blend alternatives seem to have been dropped. Note that the European Commission does not specify the use of any single refrigerant; the only restriction is that the GWP of the refrigerant selected should be less than 150.

Potential Other Alternate Refrigerants Evaluated and Reported

R152a System

Basic characteristics of the refrigerant R152a are as follows: It has a global warming potential of 124 as compared to that for R134a and CO_2 of 1430 and 1, respectively. Replacing two fluorine atoms (out of four) of R134a with hydrogen atoms makes the refrigerant R152a; the replacement of the remaining two fluorine atoms of R152a with hydrogen molecules makes it ethane. The molecular weights of R134a and R152a are 102 and 66, respectively. While R134a is nonflammable (flammability index 1), R152a is slightly flammable (flammability index 2). Hence, it could be used only in the engine compartment in a secondary loop system. In such a system, the refrigerant cools a water–glycol mixture, which is then pumped into a heat exchanger in the passenger cabin HVAC module to cool incoming air. In this case, the overall A/C system performance is about the same as that of R134a. Compared to R134a, a direct R152a system (similar to the current system except for the refrigerant change) has better cooling performance at high loads and comparable cooling performance at low loads; this advantage is not achieved in the secondary loop system. The A/C system with this refrigerant has about 33% reduced charge due to its lower density. Major components of the R152a system are the same as that of R134a except for the addition of a refrigerant-to-water glycol heat exchanger, referred to as a chiller. The current PAG lubricant is compatible with R152a. The system must be made more leak-tight since the molecule size of R152a is smaller than that of R134a. This system reduces effectively global warming potential by about 95% of the R134a A/C system. For further details, refer to Baker et al. [13].

DuPont DP1

DuPont (Minor [8]) was developing a new two-component nonflammable blend refrigerant. DuPont reported that this refrigerant met all the requirements of the European Comission regulation. The major component is a nonflammable, fluorine-based new compound, and the minor component is a commercially available refrigerant. It has zero ODP, GWP is estimated at 40, and has significant improvement in LCCP compared to that for the enhanced R134a and enhanced CO_2. Its saturation pressure–temperature characteristic is almost identical to R134a. Its critical point is 105°C (102°C for R134a), and it requires about 4% more charge and 10% higher mass flow rate compared to those for R134a for equivalent performance. It is nonflammable and easily leak detectable, similar to R134a. It is reported that this refrigerant has very encouraging toxicity results, passed initial thermal stability without any stabilizers, is stable and has excellent miscibility with PAG and POE lubricants, has excellent plastics compatibility, has excellent elastomers compatibility, and exhibits good compatibility with conventional hoses. DP1 is a direct replacement of R134a with no system changes and results in almost identical COP and about 5% reduced cooling capacity in 35–40°C ambient conditions. This refrigerant appeared to have some toxicity concerns. DuPont and Honeywell have continued joint development work on R1234yf.

INEOS Fluor AC1

This non-azeotropic refrigerant is a nonflammable refrigerant with zero ODP and GWP below 150. It has performance similar to R134a in existing systems at 35°C, i.e., COP equivalent to R134a and capacity 90–95% of R134a with only charge size and TXV modification carried out. It is compatible with existing engineering materials; toxicity results were promising (INEOS Flour [14]). This refrigerant entered the race late compared to others, and appears to have dropped out now.

Honeywell Fluid H

As mentioned earlier, Fluid H or "Blend H" is a binary azeotrope of two blend refrigerants: $CF_3CF{=}CH_2$ and CF_3I. Since it is a new chemical to match the saturation pressure–temperature characteristic of R134a, it is a drop-in refrigerant in the current system, including compressor lubricant. It is combined with a recently introduced chemical, trifluoromethyl iodide, CF_3I, a fire retardant. The following are the basic properties of Fluid H (Shankland [15]).

The global warming potential of Fluid H is less than 10; both components of Fluid H disintegrate within 12 days, compared to R134a, which takes 12 years, and the 100 years half-life of R12. Its ozone depletion potential is zero. Fluid H has a higher molecular weight than R134a (hence, it will require 20% more charge). Therefore, properly designed heat exchangers and recalibrated TXV/OT should improve the A/C system performance. Fluid H is nonflammable. This refrigerant has been found to be toxic based on the initial results, and hence it has been dropped from consideration in favor of R1234yf.

RECENT ENHANCEMENTS TO REDUCE A/C COOLING LOAD

The heat load to the passenger cabin is due to (1) solar insolation through all glass surfaces of windshield, all windows, and glass in the passenger compartment (26–44%), (2) heat conducted from the exterior metal surface of the vehicle, including roof and fire wall (12–18%), (3) heat conducted from the floor (6–11%), (4) heat load from occupants in the vehicle (16–27%) (assuming full passenger load: 4–10 adult passengers in the vehicle depending on the type of vehicle, from compact to SUVs), (5) cold air leakage from the passenger cabin to ambient (9–17%) for fresh air intake, and (6) heat load from the blower in the HVAC module (4–7%). The heat load contribution range of these components as juts provided in the parentheses is considering compact to SUV vehicles. Note that the first numbers (or the last numbers) in the ranges provided in the brackets are not additive, since the numbers are arranged for minimum to maximum range of heat load of each source. Contributions of these components vary with the vehicle size, the amount of glass area, insulation quality, and the number of passengers in the vehicle.

Keeping in mind the contributions of the first three items, the vehicle manufacturers have been working closely with the A/C system suppliers to reduce the heat load and improve the passenger comfort without impacting the passenger safety and with reducing compressor power and fuel consumption. The following enhancements are being worked on or have been implemented in the recent years, and further advancements continue in this regard:

- Reduction of solar heat load: Use of progressive tinted glasses in windshield and windows as individual laws of countries in the world permit, and use of more efficient reflecting glasses.
- Use of more efficient, lightweight insulation using appropriate thicknesses in all metal surfaces (doors, roof, floor, etc.) surrounding the passenger cabin to reduce heat load ingression into the passenger cabin. The insulation should have an optimum thickness to prevent the heat leakage to the passenger cabin. Increasing insulation over optimum thickness in the vehicle will increase the soak temperatures and may also increase underbody temperatures.
- Use of more reflective paints on vehicle exterior body to reduce the incoming heat load. This is more important for hot countries like India, Mexico, etc.
- Further improvement in the insulation of firewall, and the arrangement of engine compartment components to use efficiently underhood/underbody airflow to minimize heat conduction through the fire wall.

- Ideally, the amount of air leakage from the passenger cabin to outside ambient is designed to meet safety requirements, but not too excessive so that conditioned air leaks out of the passenger compartment to minimize further cooling in summer and heat load in winter. Typically, about $0.5x$ m^3/h cabin air is designed to leak out when the vehicle speed is x km/h; i.e., the air leakage is 25 m^3/h at 50 km/h vehicle speed.
- Heating (using electrical resistance heating) of seats in winter or cooling (using thermoelectric modules) of seats/ventilated seats in summer is used remotely just before the driver/passengers come to the vehicle or on-site after the car start. This option brings the passenger comfort right away before the cooling/heating of passenger cabin is achieved during the first 20 minutes or so. Experimental investigation has showed that optimized seat heating/cooling could improve the thermal comfort in the auto passenger cabin and broaden the acceptable cabin temperature range to be from 10.8°C to 34°C.
- Of course, the last and important but uncontrollable component of the heat load to the cabin is the heat released by human beings in the vehicle. Removal of this heat is the major reason for the A/C system.

NEW DEVELOPMENTS IN AUTOMOTIVE A/C

Some newer developments for the auto A/C are briefly summarized in this section. Major advancements have been achieved in the past decade in sensors for the control of the A/C system and component operation. Also, many incremental advances have been made in every components of the A/C system, primarily focusing on cost reduction with simplicity in design and manufacturing, improved performance, or making more compact/efficient components of the A/C system. This is beyond the scope of this article. There are a number of new ideas being evaluated by the major Tier 1 suppliers, such as:

- Separate A/C cooling for front seat driver and co-driver so that when there is only the driver in the front seat, the co-driver side A/C can be turned off.
- Hot gas heater system in which the operation of the A/C system in winter is modified such that the compressed refrigerant at compressor outlet flows to the heater (instead of or in addition to the current heater) to provide heating in the passenger cabin.
- Separating and bypassing vapor refrigerant after TXV so that only liquid refrigerant goes to the evaporator, to further make the evaporator more compact.

CONCLUDING REMARKS

A comprehensive review is made of automotive air-conditioning systems with the following brief summary:

- After briefly summarizing the current auto A/C systems, a brief historical review is made of the R12 refrigerant and early history of the A/C cars.
- Starting with the historical developments, the evolution of major components of the A/C system is provided. These components are compressors, condensers, evaporators in HVAC modules, and expansion devices.
- A number of alternate refrigerants have been proposed by various industries to replace R134a for reducing the global warming potential from 1430 to below 150. A brief description of these refrigerants is provided for their characteristics and its impact on the A/C system and global warming potential while maintaining the current performance levels. Two alternative refrigerants left for consideration/implementation by January 2011 are R1234yf and CO_2.
- Finally, briefly presented are alternatives being considered to reduce the A/C load in the passenger cabin. These alternatives would reduce the compressor power and hence the impact on the fuel consumption.

Significant improvements have taken place from the dawn of mass production of A/C systems in 1954, and now even more innovative approaches are being considered worldwide to reduce the heat load in the passenger cabin and subsequent A/C system performance reduction without sacrificing human comfort and safety. Reduction in cost and better functionality and durability/reliability are also being worked on continually.

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