AUTOMOTIVE AIR-CONDITIONING SYSTEMS – HISTORICAL DEVELOPMENTS, THE STATE OF TECHNOLOGY AND FUTURE TRENDS

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Abstract

Automotive air-conditioning system has played an important role in human comfort and to some extent safety during vehicle driving in varied atmospheric conditions. It has become an essential part of the vehicles of all categories worldwide. Even in India, 96% of all new cars manufactured in 2005 had factory-built air conditioning. After discussing the basic operation of the A/C system, in this paper, a brief summary is provided on historical development of the vehicular A/C system, refrigerant history from the inception of the A/C system to future systems: R-12, R-134a, enhanced A/C system to next generation refrigerants having no ozone layer depletion potential and negligible global warming potential. The discussion also includes the direct and indirect emissions from vehicles 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 the previous refrigerant change cost. The system design considerations are then outlined for minimizing the impact of A/C operation on the vehicle fuel consumption. Finally, new concept 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 the human comfort. It is anticipated that this paper will provide the overall and detailed prospective of the A/C system developments and provide an opportunity to the researchers to accelerate R&D for the refrigerant changeover.

Keywords: Auto air-conditioning, compressor, condenser, evaporator, TXV, orifice tube, new refrigerants

1. Introduction

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

While the A/C system provides comfort to the passengers in a vehicle, its operation in a vehicle has two-fold impact on fuel consumption: (1) burning extra fuel to power compressor for A/C operation, and (2) carrying extra A/C component load in the vehicle all the time. In addition, the A/C running depends on the climatic condition of the concerned geographical region and the time of the year. The most important impact on the fuel economy is when the A/C is running. Clodic et al. (2005) report the additional fuel consumption due to MAC operation as 2.5 to 7.5% (in USA/Europe) considering the climatic conditions, engine type (diesel or gasoline) and user profile. Corresponding CO₂ emission due to MAC operation is between 54.7 and 221.5 kg CO₂ per year per vehicle. Of course, the impact on the fuel consumption is more significant when the A/C is installed in compact and sub-compact vehicles.

In this paper, first we describe the components and operation of the current A/C systems with some details on the components as background information. 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. Next, in addition to the enhanced A/C system with R134a, the alternative refrigerants (CO₂, R-152a, and HC blends) are briefly described to replace R134a for reduction in global warming. While the auto A/C is becoming very sophisticated, the newer systems are becoming more energy efficient for the desired high performance and the cost is continually reducing with the same or better durability and reliability. Finally, some discussion is provided on ongoing efforts on A/C system heat load reduction, improvements in fuel efficiency, and fuel consumption and emission data with A/C on.
2. Basic Operation of Current Automotive A/C Systems

Two major types of A/C systems are used in the vehicles: RD-TXV and AD-OT. The components and system of a typical modern RD-TXV and AD-OT systems are shown in Fig. 1a and 1b respectively. We now describe the basic operation of this system starting with the compressor. The primary function of the compressor is to compress and pressurize gaseous cool refrigerant from the evaporator outlet with minimum compressor power, and deliver maximum amount of high-pressure high-temperature gaseous refrigerant to the condenser. These objectives are measured by isentropic and volumetric efficiencies. The compressor is powered by a drive belt from the engine. The compressor has an electrically operated engagement clutch to either turn the A/C system off or on. Next is the condenser; the condenser is located in front of the radiator. In automotive A/C systems, the condenser is typically a crossflow heat exchanger that uses air through the fins and the refrigerant through the tubes. Through the use of cool airflow provided by the engine condenser fan or ram air, the condenser cools the high-pressure hot refrigerant gas and converts it to liquid with generally a small pressure drop. The exiting liquid (subcooled in many cases) is sent via a small tube (liquid line) to a receiver-drier (RD) (applies only to an expansion valve system). The RD is a metal can with a desiccant bag inside. It is usually located near the condenser outlet pipe. Now-a-days, the RD bottle is an integral part of the condenser, and condenser is referred to as an integral receiver-drier condenser (IRDC). In this case, refrigerant passes through the RD bottle before leaving the condenser through the last pass. The objective is to improve the degree of subcooling of refrigerant at the condenser outlet. There is a negligible pressure/temperature change in the refrigerant through the RD bottle, except that the moisture is removed by the desiccant. The moisture ingress in the refrigerant loop in the A/C system can internally corrode the evaporator, thermostatic expansion valve (TXV) and clog the “orifice” of the TXV if not removed.

As the high-pressure warm liquid exits the RD/condenser, it passes through an expansion device. It can be either thermostatic expansion valve (TXV) which modulates refrigerant flow in a TXV/RD system, or a fixed diameter orifice tube (OT) in an OT/AD (accumulator-drier) system. Effectively, the TXV has a variable diameter orifice tube and OT has a fixed diameter orifice tube. Thus TXV allows more refrigerant flow at idle compared to that for the OT thus providing higher cooling. The TXV maintains desired refrigerant superheat at the exit of the evaporator. The OT cannot control the refrigerant exit condition from the OT or evaporator. 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 an evaporator in an HVAC module under the dashboard. It cools fresh or recirculated warm air, which flows into the car interior with the help of a blower. As the air is cooled in 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 tube (suction hose) to the compressor “suction” port to begin this whole process again.

3. Brief History of the Refrigerant and A/C System

With the invention of the R-12 in 1928 by GM researchers, the dawn of the automotive air-conditioning started. The first prototype self-contained system was installed in a 1939 Cadillac. Packard Motor Company in 1939 was the first company to offer complete auto air-conditioning system for cooling in summer and heating in winter using R12 refrigerant. The first bus A/C proto developed in 1934 by a joint venture between Houde
Engineering Corporation of Buffalo, NY and Career Engineering Corporation of Newark, NJ and others followed. Initial air-conditioners had a number of problems as well as Second World War hampered the production/progress. In the 1953 model year, many of the problems had been resolved and General Motors and Chrysler came back with improved air conditioning and that luxury became the necessity now for a common car owner for ever! Until then most of the A/C parts were placed in the trunk and took up whole space of trunk. In 1953, Harrison Radiator Division of General Motors came up with a revolutionary air conditioner that was totally spaced in the underhood and dashboard (eliminating it from the trunk). The use of desiccant material to absorb moisture in refrigerant line started in 1953. The following were the milestones of the development in the succeeding years (Bhatti, 1999b):

- In 1955, GM developed the first A/C and heating unit that was front mounted, totally pre-assembled and pre-tested. 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.
- In August 1965, GM crossed the five 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 oil embargo in 1973, the emphasis was placed on the fuel economy. Harrison Radiator Division of General Motors developed a cycling clutch orifice tube (CCOT) system replacing Frigidaire Valve-in-Receiver (VIR) system that resulted in the compressor off for 1/3 of the time rather than continuously running, thus improving fuel economy. By 1979 all GM vehicles used this CCOT system.
- In 1974, world came to know the ozone depletion in stratosphere due to R12 use. Harrison Radiator analyzed nine refrigerants and by 1976 arrived at R134a as the replacement of R12 eliminating chlorine. However, there was no commercial availability of R134a then; Allied Chemicals, the major company conducting research on R134a then, 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. Although the viability of R134a was proven by Harrison through wind tunnel tests on 1978 Chevrolet, the development of A/C system with R134a was discontinued due to the lack of availability of R134a till the Montreal Protocol was adopted by United Nations in September 1987. The first major revolution in the A/C system thus came starting 1990s by replacement of R-12 to R-134a to eliminate the ozone depletion in 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 changes in the A/C system: about 20% higher condensing capacity condenser (to maintain the same operating pressure so that new compressor is not needed), and change of lubricant from mineral oil to synthetic polyalkylene glycol (PAG) oil.
- Conversion from R12 to R134a in the USA, 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 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, 1300 vs 7800; carbon dioxide is the basis for global warming potential yardstick having GWP of 1. According to the European Union F-gas regulation, the refrigerant in all new A/C systems introduced in EU must have GWP of 150 or less starting 2011. Several potential replacement refrigerants are considered and the account is provided in Section 5.

4. Components of an A/C System

Major components of an automotive A/C system are: compressor, condenser, an expansion device and an evaporator as described below. In addition, tubes and hoses are required to connect these components, and controls and switches for proper operation of the A/C system and necessary shutdown conditions.

4.1 Compressors

Major types of compressors used in automotive A/C system are: reciprocating compressors (fixed displacement compressors (FDC), variable displacement compressor (VDC)), scroll compressors and rotary compressors. Fixed displacement compressors were introduced with the beginning of the A/C development. In 1950s, the compressors weighed over 27 kg (60 lbs). Today they weigh about 4-7 kg (9-15 lbs). Along with the reduction
Table 1. Important information for various compressors used in automotive air-conditioners.

<table>
<thead>
<tr>
<th>Compressor Types</th>
<th>Comp. displacement, cc</th>
<th>Comp. Power @ 1800 rpm, kW</th>
<th>Cooling Capacity @ 1800 rpm, kW</th>
<th>η\textsubscript{i} Range, %</th>
<th>η\textsubscript{v} Range, %</th>
<th>Compressor Weight, kg</th>
<th>Major Advantages</th>
<th>Major Disadvantages</th>
<th>Approx. Worldwide Business, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Displacement Compressors</td>
<td>80–200</td>
<td>1.48–3.6</td>
<td>2.94–7.2</td>
<td>45–70</td>
<td>50–69</td>
<td>4.3–7.2</td>
<td>Simple mechanism and reliable</td>
<td>Lower η\textsubscript{v} &amp; high noise due to frequent on-off</td>
<td>Approx. 66% decreasing</td>
</tr>
<tr>
<td>VDC – Intermittent Type, Variations in Steps\textsuperscript{†}</td>
<td>150–170</td>
<td>−1.76</td>
<td>−3.2</td>
<td>45–70</td>
<td>60–67</td>
<td>6.5</td>
<td>Simple mechanism</td>
<td>Performance deteriorates at part load</td>
<td>NA</td>
</tr>
<tr>
<td>VDC – Internally Controlled\textsuperscript{†}</td>
<td>120–170</td>
<td>−2.8</td>
<td>−6</td>
<td>45–70</td>
<td>60–74</td>
<td>−6.5</td>
<td>Better COP and human comfort</td>
<td>High cost and complex mechanism</td>
<td>Approx. 14% increasing</td>
</tr>
<tr>
<td>VDC – Externally Controlled\textsuperscript{†}</td>
<td>120–170</td>
<td>2.2–2.8</td>
<td>4.9–6</td>
<td>45–75</td>
<td>60–74</td>
<td>5.3–5.4</td>
<td>Better COP and human comfort</td>
<td>High cost and complex mechanism</td>
<td>Approx. 12% increasing</td>
</tr>
<tr>
<td>Scroll Compressors</td>
<td>60–115</td>
<td>1.71–2.33</td>
<td>60–80</td>
<td>85–95</td>
<td>4</td>
<td>4</td>
<td>Better η\textsubscript{v} and compact in size</td>
<td>High cost, serviceability problem</td>
<td>Approx. 12% increasing</td>
</tr>
<tr>
<td>Rotary Compressors</td>
<td>70–142</td>
<td>1.6–2.85</td>
<td>3–6.4</td>
<td>50–70</td>
<td>75–85</td>
<td>2.9–6</td>
<td>Low cost, compact in size and weight</td>
<td>Performance deteriorates at higher speeds and unsuitable for larger loads.</td>
<td>Approx. 8% increasing</td>
</tr>
</tbody>
</table>

In weight, the volumetric and isentropic efficiencies and durability/reliability have increased considerably and noise has reduced significantly. Worldwide reciprocating compressors have about 80% 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, single acting piston compressor was introduced for the A/C application, and was further improved by modifying to double acting piston compressor for more power and better efficiency. Refrigerant flow rate is maintained by the pressure differential across the suction plenum, cylinder and discharge plenum. In this compressor, the displacement (swept volume by the piston) does not vary with rpm. 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 a single acting piston. This is because there is a mechanism on the other side to change 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 besides the shaft-swash plate sub-assembly. A control valve is provided to sense the variation in heat load and change the displacement of the compressor accordingly. The variable displacement compressor is more efficient than the FDC in mild weather such as Spring/Fall, cloudy days, nights during summer season and long driving hours.

A Scroll Compressor is a rotary type compressor 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 towards the center. It can be classified as having fixed capacity and variable capacity. The advantages of this compressor are: better performance at higher compressor speeds, higher volumetric efficiency, compact and low weight, and continuous compression process ensuring smoother gas flow. Disadvantages are: very high machining accuracy essential, manufacturing of parts with complex geometry difficult, high cost and somewhat less durability, and lower performance at low rotational speeds, particularly at idle.

A Rotary Compressor 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 speeds. It has a low number of parts. Hence, its cost is low. Major advantages are: simple mechanism, less number of parts, cheapest, easy to manufacture, and better performance at idling condition. The major disadvantages are: compressor performance deteriorates at higher speeds, only applicable for lower cooling.

\textsuperscript{†} Variable Displacement Compressors (VDC): Variation in steps: 50%, 100% etc., Continuous type internally variable, i.e., Mechanical control, Continuous type externally variable, i.e., Electro-mechanical control.
requirement (small cars), and is not able to compress the liquid refrigerant.

4.2 Condensers

In a condenser, refrigerant flows on one fluid side, and the ambient air from the vehicle front grille flows on the other fluid side. The refrigerant is desuperheated, condensed and subcooled in the condenser with cooler ambient air on the other side. The refrigerant coming to condenser gains heat as follows: heat transfer in the evaporator from air to refrigerant, compressor power input and heat gains in the refrigerant lines in the engine compartment.

The following historical developments of condensers are summarized from Shah (2003) and typical condenser development is shown in Fig. 2. The mass production of the A/C system started with 1954 Pontiac at Harrison Radiator Division of General Motors Corporation, now Delphi Thermal Interior System of Delphi Corporation. After trying out different designs during 1954-1956, round tube and flat fin design condensers 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 and parallel flow (also referred to as multilow flow or headered tube-and-center) condenser. The first generation serpentine condensers were sold by Modine in 1957. Serpentine tube and corrugated louver fin condensers were introduced during late 1970s through 1980s. Their heat transfer performance is higher than that for a tube-and-fin design for equivalent airside pressure drop. The parallel flow condenser was introduced in 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.

One of the latest designs, the receiver-dryer required in the TXV-RD air-conditioning system is integrated with one of the condenser tanks thus reducing the space requirement and cost: elimination of separate mounting space for the receiver, bracket for receiver mounting, pipe connectors to connect the condenser and receiver, larger quantity of the refrigerant in the system, and additional manufacturing operations at the car assembly line. As an alternative to the extruded tubes of the parallel flow condenser, folded tube designs with internal fins are also introduced.

Since 1990s, micro fins are being used in round tubes in a round tube and flat louver fin condenser design, usually having a two tube-row depth; it increases heat transfer surface area and hence the performance. On the airside, improvements have been made in the louver designs, but the multilouver fin design is still mostly used.

In conventional automotive air conditioning systems, an RD and a condenser are separately mounted in the engine compartment. The above process and parts add cost to the air-conditioning system. By 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 further subcooled in the last pass of the condenser, thus producing more subcooling in the condenser and the resultant higher A/C system performance. Also, now only one part is manufactured thus reducing the manufacturing cost and the space requirement (associated with the RD and piping) in the engine compartment.

Fig. 2 Historical condenser developments, modified from Shah (2003).
4.3 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 at some angle greater than about 45° with the heater core. Equal or lower amount of airflow (than that going through the evaporator) can go through the heater. HVAC module design allows conditioned air to the passenger cabin in the following modes: cooling, heating, bilevel (foot/face) foot/defrost modes, and defrost/demist; depending on the design requirements, either fresh or recirculated air is used in some or all above modes.

The following is the summary of evaporator developments at GM in the USA. Between 1954 and 1960, several design changes were introduced for evaporators. Since 1960 through about 1980, the evaporator had a ribbed plate 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 airside temperature maldistribution downstream of the core due to the single-pass crossflow 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 (typical 100 mm). This core construction has been largely replaced by the plate-fin evaporator.

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. The vacuum brazing technology was replaced by controlled atmosphere brazing in 1990s by some manufacturers because the latter does not require vacuum and stringent brazing preparation, and is less costly. Two and more passes on the refrigerant side became common, allowing higher performance for an evaporator for the same packaging. Also the cup designs of the refrigerant tube plates changed from round cups to rectangular cups for improved packaging, or more heat transfer surface for given overall outside width of the refrigerant tubes. In addition, multi-louver fins replaced the split-bump fins to reduce airside 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. To minimize the condensate retention in the core, the U-channel single-tank vertical tube plate design was introduced. This design provides better condensate drainage than horizontal two-tank tube plate designs, but resulting a higher refrigerant side pressure drop and resultant slightly lower performance than the two-tank design. During 1980-present, the core depths are 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.

Fig. 3 Historical developments of Denso auto A/C evaporators.
Since 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 was extremely poor due to no cross mixing of refrigerant at a given cross section along the flow path due to flat multiport tubes; once the refrigerant evaporated in the front flow passages in the airflow path, the vapor flowed through those ports, and it resulted in excessive refrigerant side pressure drop without contributing to heat transfer. The serpentine evaporators are still used in some applications due to its lower cost and its flexibility in size/shape compared to the plate type design. The evaporator development by Denso is presented in Fig. 3 (Reddy et al. 2006).

4.4 Expansion Devices

Two most common devices used in the A/C system for refrigerant expansion are the orifice tube and thermostatic expansion valve. They are shown in Fig. 4.

The orifice tube (OT) is used as an expansion device in many vehicles. It has no moving parts (hence very low failure rates) and consists of the following: brass tube 1.40 to 1.83 mm diameter by about 38 mm long, inlet screen to block debris that could clog the OT, diffuser screen downstream to reduce noise, all molded in a nylon body. It is usually located at the inlet pipe to the evaporator, and sometimes near the condenser outlet to reduce noise in the vehicle. The OT provides a flow restriction, and thus allows isenthalpic expansion of moderate temperature high pressure liquid refrigerant at the inlet into low pressure and low temperature saturated refrigerant which then enters the evaporator. The orifice tube does not control flow. Flow is a function of the total system balance (or load). For a given OT diameter, the flow through the orifice tube is predominantly a function of subcooling and upstream pressure. The refrigerant mass flow rate increases with increasing inlet subcooling.

Thermostatic Expansion Valve (TXV or TEV) is used in the A/C system due to resulting higher performance in the A/C system, but it costs more than the OT. It is a variable diameter orifice and provides optimum/maximum cooling at more than one operating points, particularly at idle in addition to the city traffic conditions. Generally, there is more than sufficient cooling available at the highway speeds. The TXV regulates flow into the evaporator to control evaporator outlet superheat, typically preset at 3-5°C. 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 the rear evaporator since there is no second AD provided in the system.

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Fig. 4  (a) Internally controlled thermostatic expansion valve, (b) Externally controlled thermostatic expansion valve, (c) an orifice or expansion tube.
5. Alternative Refrigerants

As mentioned earlier, R134a has a significant global warming potential. EU has published F-gas final regulation to phase out R-134a from mobile A/C during 2011-2017. It also states: Replacing MAC refrigerant must have global warming potential (GWP) less than 150; there is leak rate restriction for F-gasses starting 2008 and strict inspection and repair regulations for other. US California Air Resources Board Climate Change proposed regulation to phase out R134a from heavy equipment starting 2010 and from cars starting 2017.

The desired characteristics for the new refrigerant must meet four criteria (Minor, 2006):

1. Environmental: zero ozone depletion, global potential warming index less than 150, and Life Cycle Climate Performance (LCCP) low (measured in terms of annual kg CO₂ equivalent emissions); it is currently between 150 to about 500 kg annual CO₂ equivalent total emissions (direct and indirect) based on major cities/countries around the globe (Hill, 2006).

2. Performance: It must have all the required/desired performance characteristics in a vehicle, such as: desired performance in all vehicles and in all climates, compatible with the existing A/C systems so that there are practically no changes required in the components and systems, must be energy efficient, must have proper lubricant, and it must be compatible with the materials and thermally stable. Worldwide search has resulted in the following four new refrigerants as potential refrigerants for the replacement of R134a: CO₂, R152a, Honeywell Fluid H and DuPont DP-1. A brief description of these refrigerants follows.

3. Safety: It must pass through the safety regulation of regulatory agencies: Toxicity tests and the flammability index must be less than 2.

4. Viability: It must meet EU F-gas directive. Raw material should be available and manufacturable. Cost effective transition for the entire value chain, and must be a global industry solution.

5.1 CO₂ (Carbon Dioxide) System

The carbon dioxide started as a refrigerant 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 R-12 in 1928 by GM researchers and subsequent other refrigerants, CO₂ was again replaced by 1940s to R22, R12, etc., and now again it is being considered as a “new” refrigerant.

The advantages of the CO₂ as a refrigerant are as follows: GWP = 1, non-HFC/natural fluid, non-flammable, 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 CO₂ is higher than that for R-134a due to the following reasons: The A/C system works in transcritical region of the fluid at very high operating pressures (about eight times higher than that for R-134a). This requires heavy A/C system components compared to those for R-134a, resulting in fuel penalty due to carrying heavy components in the vehicle all the time and requiring more fuel to operate the A/C. Equivalent global warming potential of CO₂ system is higher than that for current R-134a system. Other disadvantages of the CO₂ system are as follows: new designs required for all system & components, high tooling/production costs, additional components needed, safety system needed, increased system weight, full efficiency potential needs to be demonstrated, system leakage a very serious problem due to extremely small molecule size of CO₂ and ultra high operating pressures, leak detection method needed, and training of personnel.

5.2 R-152a System

Basic characteristics of the refrigerant R-152a are as follows: It has the global warming potential of 120 compared to that for R-134a and CO₂ as 1300 and 1, respectively. By replacing two fluorine atoms (out of four) of R-134a with hydrogen atoms makes the refrigerant R-152a. The molecular weights of R-134a and R-152a are 102 and 66, respectively. While R-134a is non-flammable, R-152a is slightly flammable, and hence, its implementation in the A/C requires safety considerations, unless used in a secondary loop in the engine compartment. In that case, the A/C system performance will be about the same as that of R-134a. Leak detection device will be needed in the passenger compartment with R-152a system. Compared to R-134a, R-152a has better cooling performance at high loads and comparable cooling performance at low loads. The A/C system with this refrigerant is about 10% more energy efficient with reduced charge (about 30-35%) due to lower density. Components of the R-152a system are the same as that of R134a as well as the cost of the system is about the same. Primarily, a compatible lubricant is needed as well as the system must be made more leak tight since the molecule size of R152a is smaller than that of R134a. It has the same potential for improved efficiency as that for R 134a, and its system reduces effectively global warming potential by about 90% of the R-134a A/C system. For further details, refer to Baker et al. (2003).
5.3 Honeywell Fluid H

Fluid H or “Blend H” is an azoetrope of two blend refrigerants: (1) a newly created man-made molecule called 1,1,1,2-tetrafluoropropane CF₃CF=CH₂ or also known by its catchier number “1234yf” not yet manufactured, and (2) trifluoromethyl iodide, CF₃I, a fire retardant produced in small quantities. Since it is a man made chemical to match the saturation pressure-temperature characteristic of R134a, it will be a drop-in refrigerant in the current system including compressor lubricant. It is combined with a recently introduced chemical, trifluoromethyl iodide, a fire retardant. The following are the basic properties of Fluid H and R-134a.

<table>
<thead>
<tr>
<th>Refrigerant Type</th>
<th>H</th>
<th>134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point, T_b</td>
<td>-30°C</td>
<td>-26°C</td>
</tr>
<tr>
<td>Critical Point, T_c</td>
<td>97°C</td>
<td>102°C</td>
</tr>
<tr>
<td>P_vapor, kPa (5°C)</td>
<td>381</td>
<td>350</td>
</tr>
<tr>
<td>P_vapor, kPa (65°C)</td>
<td>1795</td>
<td>1890</td>
</tr>
<tr>
<td>Flammable</td>
<td>No*</td>
<td>No*</td>
</tr>
<tr>
<td>GWP_{100}</td>
<td>&lt; 10</td>
<td>1300 (CF₃CF=CH₂ ≤ 3-6, CF₃I ≈ 1)</td>
</tr>
<tr>
<td>Atmospheric life time</td>
<td>&lt; 12 days</td>
<td>12 years (CF₃CF=CH₂ = 12 days, CF₃I = 4 days)</td>
</tr>
</tbody>
</table>

*ASHRAE Std. 34 & SAE J1657

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 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), and therefore, properly designed heat exchangers and recalibrated TXV/OT should improve the A/C system performance. Fluid H is non-flammable and non-toxic (and hence legal to vent during recharging of the system). The toxicity tests are being conducted and may take about 2-3 years for completion. The cost of this new blend refrigerant will be higher, but the premium will be lot less than that for CO₂.

5.4 DuPont DP-1

DuPont (Minor, 2006) has announced a new refrigerant which meets all the requirements of the European Union (EU) regulation. It has zero ODP, GWP is estimated at 40 and has significant improvement in LCCP compared to that for the enhanced R134a and enhanced CO₂. Its saturation pressure-temperature characteristics is almost identical to R134a. Its critical point is 105°C (102°C for R134a), about 4% higher charge and 10% higher mass flow rate compared to those for R134a. It is easily leak detectable similar to R134a. It has excellent toxicity results, excellent thermal stability without any stabilizers, stable and excellent miscibility with PAG and POE lubricants, excellent plastics compatibility, excellent elastomers compatibility, and exhibits good compatibility with conventional hoses. DP-1 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. The development work continues.

5.5 INEOS Fluor Refrigerant

This refrigerant is a non-flammable refrigerant with zero Ozone Depletion Potential (ODP) and Direct Global Warming Potential below 150. It has similar performance to HFC134a in existing systems (Ineos Flour, 2006). No further details are provided at this time.

6. 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 full capacity passengers in the vehicle (16-27%) (assuming 4-10 adult passengers in the vehicle depending on the type of vehicle from subcompact to SUVs), (4) cold air leakage from the passenger cabin to ambient (9-17%), and (5) heat load from the blower in the HVAC module (4-7%). The contribution range of these components are provided in the brackets considering subcompact to SUV vehicles. As one finds contributions of these components varies 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. The following enhancements are being worked on 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 country laws permit, and use of more efficient reflecting glasses.
- **Use of more efficient, lightweight insulation using appropriate thicknesses in all metal surfaces (doors, roof, etc.) surrounding the passenger cabin to reduce heat load ingress into the passenger cabin. 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 arrangement of the 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 requirement of the state and country, 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.**

Of course, the last and important but uncontrollable component of the heat load to the cabin is the heat released by human beings.

In order to provide comfort with minimum A/C power consumption, ventilated seats are being considered for passenger cooling and heating to further reduce/increase the passenger cabin heat load for summer/winter conditions, respectively.

### 7. Concluding Remarks

A comprehensive review is made of automotive air-conditioning systems. After briefly summarizing the current auto A/C systems, a brief historical review is made of the refrigerant from R12 to R 134a to a number of alternative refrigerants being considered now to reduce the global warming potential. Similarly, starting with the historical developments, the evolution of major components of the A/C system is provided. These components are: compressors, condensers, evaporators, and expansion devices. Five alternate refrigerants have been proposed by various industries to replace R134a to reduce the global warming potential from 1300 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. Finally, alternatives being considered to reduce the A/C load in the passenger cabin are briefly presented. These alternatives would reduce the compressor power and hence the impact on the fuel consumption. Significant improvements have taken place from the dawn 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. Reduction in cost and better functionality and durability/reliability are also being worked on.

### References


