

Scegli oggi la tecnologia di domani.  
Liderando a tecnologia do amant  
Technology  
Pour conduire aujourd'hui la technologie de d  
Liderando a tecnologia del mañana  
未来のテクノロジーに  
Liderando a tecnologia del mañana

**DELPHI**

**DELPHI**

## Introduction

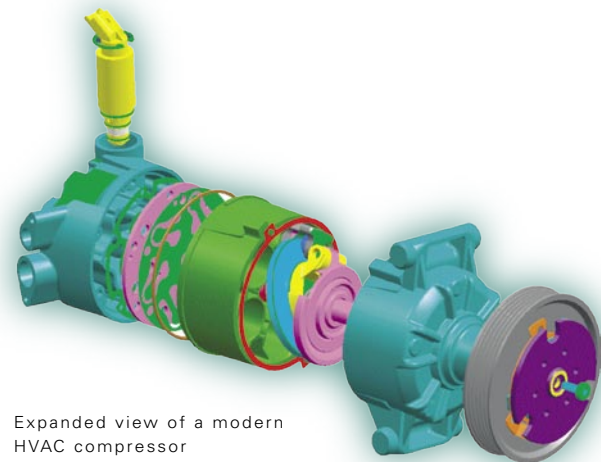
The passenger compartment of a modern automobile offers a very different environment to that of a vehicle from fifty years ago. As well as the ergonomically designed seating and instrument layout, the all round visibility and the efficient use of space, today's passenger has control over air tem-

perature, quality and movement in all corners of the vehicle. The modern heating, ventilating and air conditioning system (HVAC) can ensure that thermal comfort and all round visibility are delivered in environments that range from the heat of Phoenix Arizona to the coldest Scandinavian winter.



View of instrument panel and HVAC controls

The very heart of the air conditioning system is the compressor. Its key tasks are to generate the required flow of refrigerant around the system and at the same time to compress it sufficiently to raise its temperature above the ambient in order that heat can be rejected from the system. These demands must be met efficiently over very wide ranges of compressor speed and ambient conditions. At the same time very demanding noise generation constraints and expectations of durability have to be met.



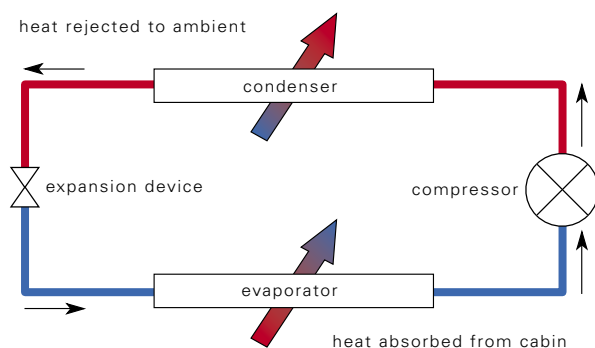
Expanded view of a modern HVAC compressor

## Air Conditioning Cycle

It is self evident that heat tends to flow from high temperature to low. If we wish to provide cooling at a location in a high temperature environment then we are effectively asking heat to flow from low temperature to high. To achieve this it is necessary to operate a thermodynamic cycle in which a

refrigerant at a low temperature is used to extract heat from the location to be cooled. The refrigerant is subsequently compressed until it becomes hot enough to be able to reject heat to the ambient. After cooling to near ambient temperature by the ambient air, it is expanded back to low pressure, a process which generates further refrigerant temperature reduction that becomes low enough to be used for cooling at the required location. The cycle is complete. The

required cooling is thus achieved but at the expense of the work necessary to drive the compressor.



Schematic of air conditioning cycle

## The Automotive Air Conditioning Application

The automotive application places very special demands on the air conditioning system. A typical vehicle system has a similar cooling capacity to that required for the air conditioning of a small house despite the vast difference in volumes to be cooled. The reasons for this are twofold. Firstly cooling duty per unit volume is much higher for the vehicle because heat transfer coefficients between hot ambient air and the outside surfaces are much higher due to movement of the vehicle through the air. Secondly the proportion of the enclosure consisting of glass is very high for the vehicle – a factor that makes the effect of direct solar radiation heating very high. On top of this a particularly demanding requirement is to cool the cabin very rapidly after the vehicle has been soaked in an ambient temperature of 40°C or higher. At the start of the cool down temperatures in the cabin can be as high as 60 or 70°C.

Another significant way in which automotive air conditioning differs from the domestic or commercial version is the question of compressor drive. In the vehicle the compressor is belt driven by the engine so that independent control over the compressor speed is not possible. This obviously has significant implications for system control and means that there can be calls for high system performance at times when the compressor speed is very low. An important

implication of this is that the compressor drive shaft must pass out of the compressor casing with the resultant potential for refrigerant leakage. Hermetic compressors are not possible and very effective shaft seals must be used. A second implication of the external drive is that the compressor must be engine mounted so that lengths of flexible hose must be introduced to accommodate relative movement between engine and chassis mounted components.

As with other air conditioning applications system efficiency is very important and the automotive application is no exception. While the characteristics of all the major components in the system contribute to overall efficiency any compressor inefficiencies must be kept to a minimum. A further feature of the compressor that requires serious consideration is its intrinsic noise generation - modern vehicle noise requirements mean that the compressor must be very quiet and vibration free.

And finally, three further requirements of the compressor, specific to the automotive application, but which apply equally to every vehicle component – are stringent constraints on size, weight and cost.



The challenge of compressor packaging

As a result of all these constraints deriving from the use of an engine driven compressor, it is often suggested that an electrically driven system would provide a much better solution. The reason that it is not feasible on current vehicles is insufficient electrical power is available and its application must await the widespread implementation of high powered and efficient integrated starter/generators. The applications in which an electrical compressor would make real sense however are in hybrid and fuel cell vehicles where sufficient electrical power is readily available.

The high efficiency of modern engines can lead to the situation in which insufficient rejected heat is available for comfort heating. This fact has prompted the suggestion that the air conditioning system be operated in reverse as a heat pump to supplement the engine heat and the viability of the concept has been demonstrated on a number of platforms. The implications for the compressor are that the required operating life can be nearly doubled and the compressor ambient safe operating temperature range must be extended downwards to minus 20°C.

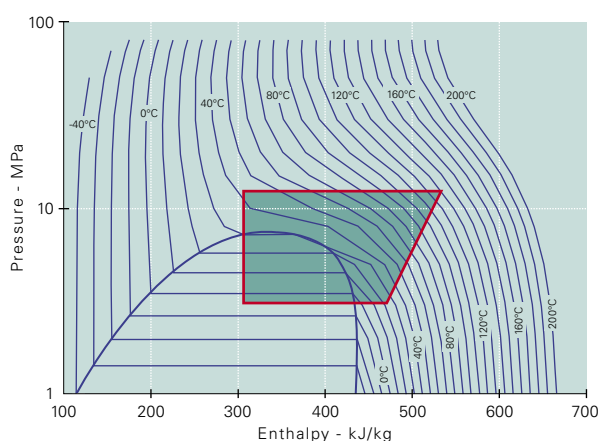


Delphi vehicle with Heat Pump supplementary heating

## Refrigerant Issues

The automotive air conditioning industry responded pro-actively to the demands of the 1987 Montreal Protocol and by 1994, 2 years early, the change over from R12 to R134a was complete for all vehicle production lines in the developed world. It soon became apparent that this may not be the end of the story and with increasing penetration of air conditioning in the European market together with the demands of the Kyoto Protocol pressure has built to make changes to still further reduce the potential contribution of air conditioning systems to global warming. A new Directive has recently completed its progress through the European legislative process. It requires the elimination of R134a from all new models from 2011 and from all new vehicles by 2017. The currently considered alternatives are R152a with a global warming potential less than 10% of that of R134a, or the so-called 'natural' refrigerant R744 (carbon dioxide). R152a has thermodynamic characteristics very similar to those of R134a and will be directly usable with current compressor technology. Its potential draw back is a degree of flammability that has made the industry reluctant to consider it. More recently other large chemical companies have announced the potential availability of new alternatives. Little is known about them at this stage but it is assumed that they too would function with current compressor technology. There must be a question as to whether the necessary development and

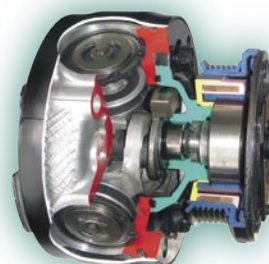
testing and then implementation of the necessary manufacturing capacity can be completed in time to meet the requirements of the European legislation. If R744 becomes the chosen route the implications for compressor technology are very far-reaching. Air conditioning systems with R744 need compressors with displacement of only a fifth of that required for R134a but operating at much higher pressures. Discharge pressures of 120 bar are normal compared with a typical 18 bar for an R134a system. As can be imagined, these factors have big implications for the compressor layout and structural strength requirements and also represent a particularly severe shaft seal challenge.



Idealized pressure enthalpy diagram of CO<sub>2</sub> cycle

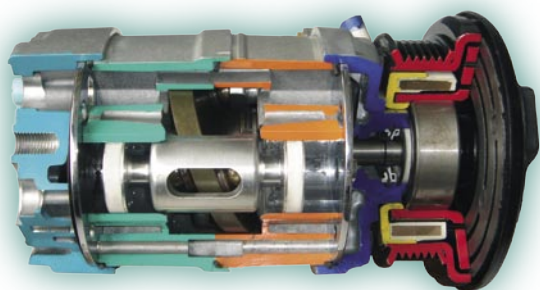
## Compressor Technologies

Air conditioning began to become available for vehicles in the early 1950s. From the beginning a number of different compressor technologies have been used. The earliest systems used piston compressors in various configurations. The Frigidaire F5, a five piston wobble plate configuration, used in the earliest GM vehicles with air conditioning was first produced in 1956 – it weighed in at 18kg! The R4 compressor with a scotch yoke mechanism was first produced by Harrison (now Delphi) in 1974 and remained in production until 1995. It was 190mm in overall diameter and weighed 9kg.



An early compressor, the Delphi R4

The preferred configuration for a piston compressor soon moved to a double acting swash-plate design of which the Harrison (Delphi) HD6 is typical. The fixed swash-plate is held between the opposing ends of the double piston by a pair of shoes and two steel balls.



Section through an early fixed swash-plate compressor, the Delphi HD6

A second positive displacement configuration used is the sliding vane. It offers advantages of compactness and low cost but carries the penalty of very poor efficiency at high pressure ratios.

The other main configuration is the scroll compressor in which one scroll with an involute surface orbits inside a fixed second scroll of the same shape. It can be seen from the figure that the contact points of the scrolls enclose a cavity of reducing size (shaded green) that moves from the outside to the centre as the one scroll orbits inside the other. The result is an induction of gas at the periphery of the scroll and delivery of compressed gas at the centre. These compressors are very efficient and quiet but represent a significant challenge for manufacture and hence for cost. They have the disadvantage that although a variable version of this compressor is possible, the superior efficiency advantage is lost.

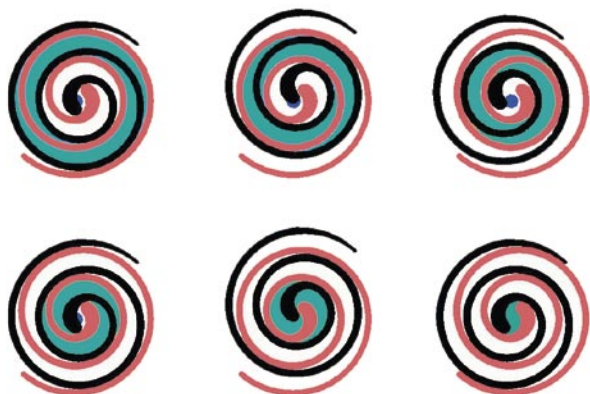
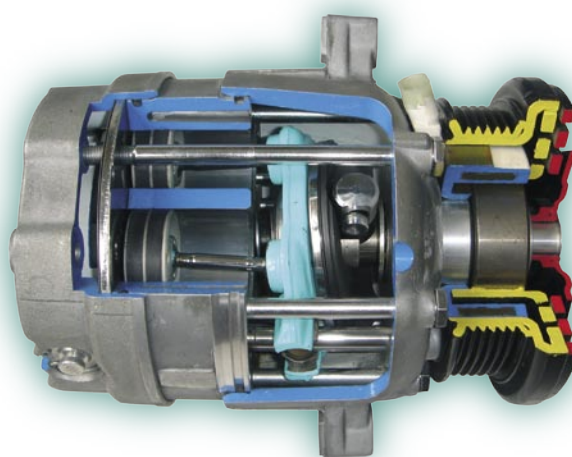


Illustration of Scroll compression process

Early compressors were all fixed displacement and system control was achieved by switching the compressor on and off by means of an electro-mechanical clutch contained within the compressor pulley. As consideration began to be given to the application of air conditioning to smaller vehicles with smaller engines it was found that the significant and sudden increase in engine load that resulted from compressor switching caused problems for the small engine with resultant issues of drivability. A compressor with variable displacement offered the solution to this problem. In 1985 Harrison (Delphi) were the first to go into series production with a variable compressor, the V5, a wobble plate design with five pistons.



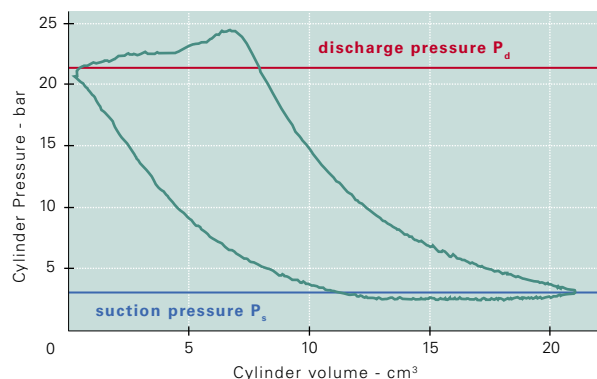
The mechanism of a variable wobble plate compressor

Although scroll, vane and piston compressors are all still in use in automotive applications, the piston compressor is dominant. Where the combination of efficiency and controllability is the key requirement, piston compressors offer the best solution.

## Piston Compressors

The compressor has the task of inducing gas at a low suction pressure and delivering it at a higher discharge pressure. It achieves this by using reed valves that operate automatically to control the fluid flow into and out of the cylinders. Starting with the piston at top dead centre the pressure in the small clearance volume will be close to the discharge pressure as the piston has just delivered its charge. As the piston recedes and the pressure in the clearance volume falls, the delivery reed valve closes automatically, driven by the discharge pressure. Since the clearance

volume is small, the pressure drops quickly until it is below the suction pressure. At this stage the intake valve opens and the further movement of the piston induces fresh charge.



Indicator diagram for swash-plate compressor

After bottom dead centre the piston compresses the gas induced into the cylinder until it reaches the discharge pressure. At this stage the delivery valve is opened automatically by the pressure differential and the compressed charge is delivered.

There are several key features of this overall process important for performance and efficiency. The clearance volume must be as small as possible without risking interference between the piston and the cylinder head as a result of differential thermal expansion or stress effects. The consequences of finite clearance volume are principally indicated by the compressor volumetric efficiency which is the ratio of the volume of delivered gas measured at the suction pressure relative to volume displaced by the piston. The dynamic response characteristics of the reed valves are also important. Volumetric efficiency is also impacted by the quantity of gas that leaks past the pistons to the crank case, which is determined by piston sealing and clearances.

Efficiency	Definition
volumetric $\eta_v$	$\frac{\text{delivered volume}}{\text{displaced volume}}$
isentropic $\eta_s$	$\frac{\text{ideal minimum work needed}}{\text{work done to compress gas}}$
mechanical $\eta_m$	$\frac{\text{work done on compressed gas}}{\text{work input to compressor shaft}}$

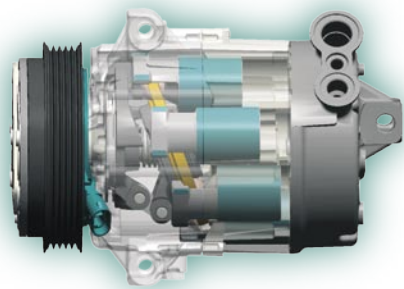
Table of compressor efficiencies

The second measure of compressor performance quality is the isentropic efficiency. It is given by the ratio of the theoretical minimum work required to compress the gas from suction to discharge pressure relative to the work actually done. The theoretical minimum is based on an idealized 'isentropic' process in which no turbulence generation or viscosity effects occur. The third measure of compressor performance quality is the mechanical efficiency. This is the ratio of the work actually done on the gas relative to the measured power input to the compressor shaft. The difference between these two figures is due to friction.

## Variable Piston Compressors

As stated above, Harrison (now Delphi) was the first to go into series production with a variable compressor. The wobble plate that drives the pistons with this design is free to tilt so that the piston stroke, and hence displacement can be changed. The wobble plate mechanism allows very short and compact pistons to be used. The ball-ended connecting rods are swaged into the pistons and wobble plate which results in strong, low friction and very simple joints. The fact that the connecting rods are tilted slightly during compression as a result of the wobble plate movement means that the forces acting do not all lie along the piston axes. The result is that higher vibrational harmonics can be generated which makes management of compressor noise more of a challenge than with later generations of swash-plate compressor. Nonetheless the value of this configuration is illustrated by the fact that it is still produced at a rate of several million units per year worldwide for installation in new vehicles as original equipment, offering a good compromise between cost and the functionality of a variable displacement compressor.

The next generation of variable compressors used a swash-plate mechanism, largely because of its advantages of low vibration and noise. The mechanism by which the compressor displacement is controlled can be described in principle relatively simply, but in fact the actual displacement of the compressor in any given situation results from a quite complex interaction of forces.



Variable swash-plate compressor showing mechanism

The swash-plate has a linkage mechanism that allows it to rotate thus changing its angle and with it, the piston displacement. The linkage is designed so that the clearance volume remains as constant and small as possible over the full swash-plate angle range from full stroke to minimum stroke.

This swash-plates freedom to rotate means that under any given operating conditions it will take up a position that is determined by the balance of all the forces acting on it that tend to cause it to rotate about its centre of rotation. The first element of complexity is that the centre of rotation is not fixed as it shifts location slightly with the swash-plate angle. It lies fairly near to the swash-plate connection with the link but its exact locus is a function of the linkage mechanism location, dimensions and of the swash-plate angle. The most obvious force that comes into play is the gas pressure acting on the piston crown. Estimation of its average effect, however is complex as the cylinder pressure varies greatly around the cycle. At the same time its line of action is continually changing and hence so is the effective torque it exerts about the centre of rotation. This torque will obviously tend to upstroke the compressor.

A less obvious source of torque generation on the swash-plate is the inertia of the pistons which are repeatedly accelerated and decelerated as the compressor is operated. It might be thought that the effect of the forces for acceleration and deceleration cancel each other out but in fact the piston

is accelerated upwards over the half of the swash-plate furthest from its centre of rotation and correspondingly decelerated over the half nearest to the centre of rotation. The former therefore exerts greater torque and the net result is a tendency to upstroke which is proportional to the square of the piston speed and thus becomes significant at higher compressor speeds.

A second torque generating force that is a similar function of compressor speed comes from centrifugal affects acting on both the link mechanism and the swash-plate itself. If one considers the two halves of the swash-plate nearest and most remote from the centre of rotation it is clear that the centrifugal forces of the more remote half generate the greater torque and the net result will be a tendency to destroke the compressor.

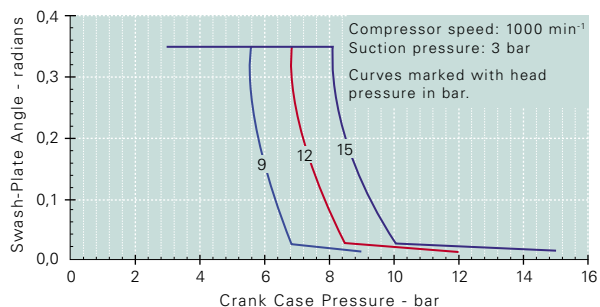
Further forces generating rotation torque can come from the fitting of upstroke and/or downstroke springs. These can be installed on the shaft to assist the upstroke/downstroke process under some compressor operating conditions and if fitted will obviously contribute to the overall balance of torques. Here the effect will be a simple function of the swash-plate angle.

The final contributor to the balance of torques is that generated on the underside of the pistons by the crank case pressure. Although the crank case pressure remains constant around the cycle its line of action around the plate must be integrated to obtain an average net torque. It is the ability to control this pressure that allows the balance to be shifted and thus the swash-plate angle to be controlled. Crank case pressure is controlled with bleeds from both suction and high side. The small suction bleed is usually permanent and the high side bleed is controlled by means of a valve. If the high side bleed is closed the suction bleed pumps the crankcase down to suction pressure with the result that the compressor operates at full

Mechanism	Effect	Comment
Cylinder pressure	Upstroke	Integrated around swash-plate
Piston inertia	Upstroke	Significant at high speed
Centrifugal forces	Destroke	Significant at high speed
Springs	Upstroke/destroke	Where fitted
Crank case pressure	Destroke	Adjusted for control

Table of swash-plate torque generating mechanisms

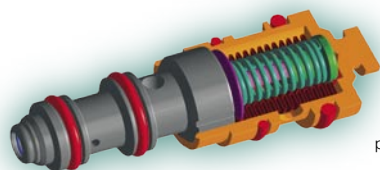
stroke. If the discharge pressure gets too high, the high pressure bleed can be opened and the crank case pressure increases. At some stage it will be high enough for the balance of torques to destroke the compressor. The control has been achieved.



Compressor control curves

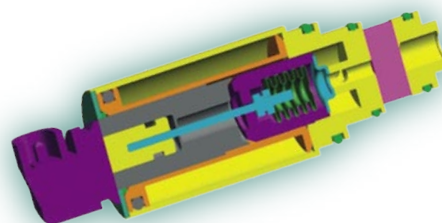
The high pressure control valve can be an automatic, spring operated valve or an electrically switched and electronically controlled valve. The former configuration is known as pneumatic control, the latter is called external control.

The dominant element of system control is the thermal expansion valve that acts to maintain a given degree of superheat of the refrigerant leaving the evaporator. If the evaporator pressure becomes too low and the risk of evaporator freezing occurs, the pneumatic control valve comes into operation to reduce the compressor stroke and maintain the required evaporator pressure. The automatic control mechanism comes from the bellows which is under permanent vacuum on its inside and exposed to the suction pressure on the outside. If this pressure differential falls too low due to low suction pressure the bellows expand to drive the needle to open the connecting passage between discharge pressure and crank case. The resulting increase in crank case pressure leads to a reduction in stroke with the consequential reduction in refrigerant mass flow rate and increase in suction pressure. As the evaporator pressure increases the pressure differential drives the needle to close the connecting passage between discharge pressure and crank case. The crank case pressure falls as a result of the suction bleed and the compressor stroke increases.



Section through pneumatic compressor control valve

The use of external control gives an extra degree of flexibility. Pneumatic control maintains evaporator pressure so that air-off temperatures remain a few degrees above 0°C and any need for higher temperatures than this are achieved by mixing with warm ambient or recirculated air. As a result more compressor work is done to cool the air down to the low temperature than is really necessary. Very significant energy savings can be made by using the external control to manage the system capacity so that only sufficient cooling is provided to meet the real need so that significant reheating of the comfort air is not needed.



Section through electronically controlled compressor valve

This potential for energy saving is the most important aspect of external electronic control but it also offers other advantages such as de-stroking at system shut down so that the engine load felt by the engine at system start-up can be gradually increased – known as “soft start”. A further advantage is the ability to exercise a degree of control over cabin humidity and avoid excessive dryness that can occur with simple pneumatic control.

Fixed compressors have electromagnetically operated clutches to allow system control by switching the compressor drive on and off as required. Variable compressors have traditionally retained the clutch to be able to turn the system off when not required or should system conditions approach unsafe operating levels for any reason. A more recent innovation is the introduction of clutchless compressors. It is made possible by the implementation of external compressor control. Here the compressor can be destroked to such an extent that it no longer pumps and can be permanently driven without dissipation of significant energy. Typical destroked energy consumption is only 150W at 3000rev/min. Very small stroke can be relatively easily achieved and the challenge is to activate upstroke again when required. The advantages are principally packaging and weight although cost savings are also possible.

## A Compressor Range

One frequently hears a need expressed with phrases such as: "I want the most efficient and lightest component possible." In reality however, it is not possible to optimise against two independent parameters at the same time - the most efficient possible will not necessarily be the lightest and vice-versa (other than by coincidence). While optimisation against a single parameter is possible, the significance of the second can only then be expressed as a limit or a constraint. "I want the most efficient component possible weighing less than 1kg."

It is generally recognised that the automotive industry sources against the single optimisation parameter – cost. While there are very many other constraints within which they have to operate – both applications and market based constraints – these can only be expressed as limiting values. The target will always be to acquire the product that meets the needs of the application at the lowest possible cost. Since the needs expressed as constraints vary greatly, depending upon application, a supplier needs to offer an extensive range of compressors offering a spectrum of balances between sophistication and cost in order to stand a chance of meeting the needs of a significant proportion of the market. This will extend from simple fixed compressors to electronically controlled variable compressors where performance, accuracy and efficiency play a more important role.

As means of illustration the Delphi compressor product range for R134a is indicated below. Compressors are shown with the

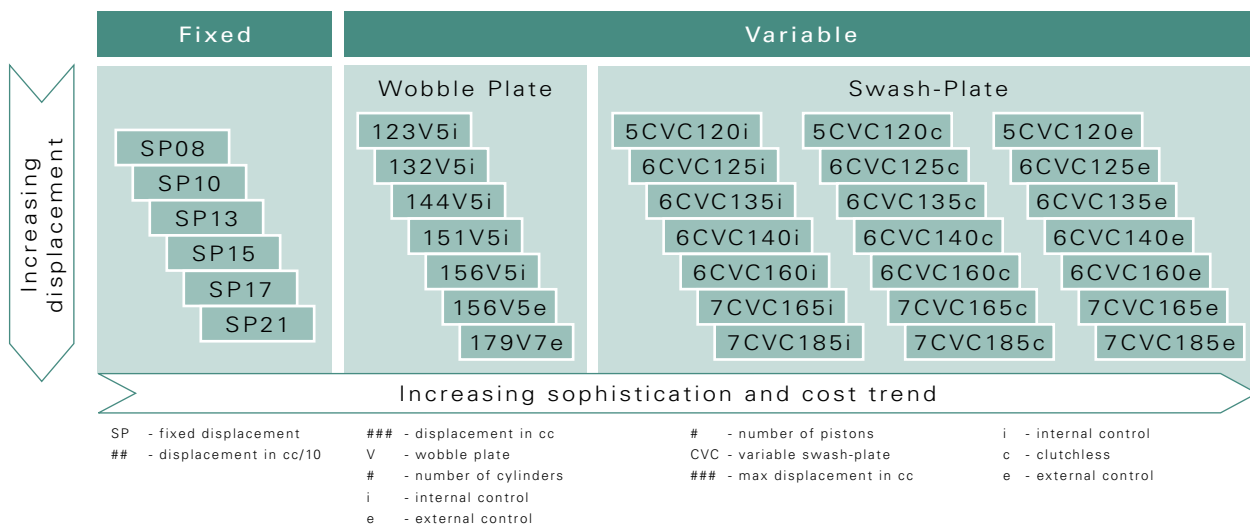
trend for both increasing sophistication and cost going from left to right and increasing displacement going from top to bottom.

The SP range of fixed swash-plate compressors each with five double acting pistons represents the lowest cost solution for applications that can tolerate the implications of a cycling clutch. The double piston configuration means that in effect there are a total of ten compression cavities which yields very low levels of pressure fluctuation. This feature combined with the smoothness of the swash-plate drive results in an inherently quiet compressor.

The V5 range of wobble plate variable compressors has already been described as the original Delphi variable compressor. It has seen considerable refinement over the years and whilst it cannot compete with the CVC swash-plate range for quietness and efficiency it represents a very cost-effective introduction to variable compressor technology. The dual PTFE piston rings contribute to low blow-by and good oil retention.

The Compact Variable Compressor (CVC) range of compressors uses swash-plate technology to ensure that a/c system generated noise and vibration is kept to a minimum. Internally and externally controlled versions are available.

The externally controlled range of CVC compressors are offered with and without clutch. In the clutchless compressor the ability to upstroke again after destroke to a minimum that is only 1 or 2% of maximum stroke is ensured by the very tight tolerances of the piston and cylinder bore dimensions. They ensure very low blow-by which helps maintain low parasitic losses and ensure that upstroke can be achieved when required.



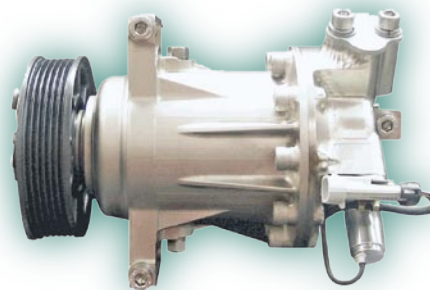
Delphi engine-driven R134a compressor range

It can be seen that the CVC range is very comprehensive. Not shown here is the further flexibility offered by a very wide range of possible piping configurations which together carry the implication that a large number of different compressor configurations must pass down the production lines. It has been concluded by some that this complexity is likely to have a negative effect on product quality when in fact the opposite is true. To manage the complexity a system known as RFID – radio frequency identification – is used in which each individual compressor carries a chip with it down the production line. During the passage down the line the chip reads and verifies all the information about the individual components as they are assembled (manufacturing dates, dimensions, etc) and communicates it back to a central computer for filing. This data on each individual compressor is then available for later access should there be problems further down the line or problems from the field. The availability of all this comprehensive and detailed data contributes to the establishment and maintenance of the very high levels of reliability required by the application.

## New Technologies

In recent years a serious interest in the use of R744 as refrigerant in automotive air conditioning systems has been generated. European legislation has recently been passed that will force the industry to move away from R134a and R744 has become the leading contender. As a result Delphi is developing a range of swash-plate compressors to meet this need. Current prototypes have five pistons and maximum displacement of 30cc although the number of pistons in the final product range is still under development. Both fixed and variable versions of displacements of 15, 21 and 30cc are planned. It is envisaged that for low displacement the number of pistons will be between 5 and 7, at the high end it

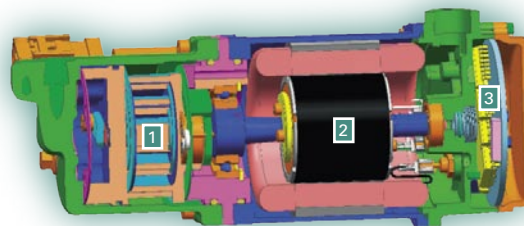
will be between 7 and 9. The reason for this uncertainty is that the appropriate balance between cost and noise/durability has not yet been established.



Delphi CO<sub>2</sub> compressor

It can be seen that as a result of the very different fluid properties, the displacements offered are very much lower than for R134a. The range features shaft sealing by face seal and internal oil separator. The need for the latter comes from the significant evaporator performance degradation that occurs with CO<sub>2</sub> if excess oil is allowed to circulate.

The second new technology concerns compressors for future powertrains, whether hybrid or fuel cell – the electrically driven compressor. Under development is a family of scroll compressors driven by 315 volt brushless electric motors. Scroll displacements are 28 and 38cc for cooling capacities of 5.6 and 7.1 kW respectively. The motors are cooled using the low temperature refrigerant vapour from the evaporator with a resultant motor efficiency of 94%. The inverter is cooled by conduction from the same refrigerant and it too has efficiency in the 94 to 98% range.



Section through Delphi Electric Compressor

- 1 Scroll Compressor
- 2 Permanent Magnet Motor
- 3 Inverter and Integrated Electronics

## Conclusion

This paper has aimed to present the technical requirements of the compressor for use in automotive air conditioning applications and to show how the diverse requirements of the application mean that a supplier must have available a range of technologies and specifications to be able to meet these needs. It goes on to show how the Delphi compressor product range is designed to give comprehensive coverage and finishes with consideration of compressors for developmental technologies that are likely to become significant in the relatively near future.

**Delphi Thermal Systems European Headquarters**

Avenue de Luxembourg  
L - 4940 Bascharage  
Grand-Duché de Luxembourg  
Tél: +352 50 18 1  
Fax: +352 50 18 48 00

**DELPHI**

Driving Tomorrow's Technology

[www.delphi.com](http://www.delphi.com)