1 Air-conditioning fundamentals

The aim of this chapter is to:

- Give an overview of the historical development of the heating and ventilation system and introduction of the air-conditioning (A/C) system.
- Provide the reader with a case study on the design and optimisation of an air-conditioning (A/C) system.
- Enable the reader to understand the fundamental principles and operation of the heating, cooling, ventilation and air-conditioning system.
- Introduce the possible replacement refrigerant/system to R134a.

1.1 History of automotive air-conditioning systems

The early history of transportation systems starts mainly with the horse drawn carriage. This was eventually surpassed by the invention of the automobile. Early automobiles had cabin spaces that were open to the outside environment. This means that the occupants had to adjust there clothing to allow for different weather conditions. Closed cabin spaces were eventually introduced which required heating, cooling and ventilating to meet customer expectations. Early heating systems included heating clay bricks and placing them inside the vehicle or using simple fuel burners to add heat to the vehicle's interior. Ventilation inside the vehicle was achieved through opening or tilting windows or the windscreen; vents were added to doors and bulkhead to improve air circulation and louvered panels were the equivalent to our modern air ducts. Air flow was hard to control because it was dependent upon the vehicle speed and sometimes would allow dirty, humid air which contained fumes from the engine compartment. Cooling could be as simple as having a block of ice inside the vehicle and allowing it to melt! Eventually a number of design issues were overcome, these included air vents at the base of the windscreen for natural flow ventilation and electric motors to increase the flow at low speeds. Eventually heat exchangers were introduced which used either the heat from the exhaust system or water from the cooling system as a source, to heat the inside of the vehicle cabin. Early cabin cooling systems were aftermarket sourced and worked on evaporative cooling. They consisted of a box or cylinder fitted to the window of the vehicle. The intake of the unit would allow air to enter from outside and travel through a water soaked wire mesh grill and excelsior cone inside the unit. The water would evaporate due to absorbing the heat in the air and travel through the outlet of the unit which acted as a feed to the inside of the vehicle. The water was held in a reservoir inside the unit and had to be topped up to keep the cone wet otherwise the unit would not operate. The air entering the vehicle would be cool if the relative humidity of the air entering the unit was low. If the relative humidity of the air was high then the water could not evaporate. When the unit was working effectively it would deliver cool saturated water vapour to the inside of the vehicle which raised the humidity levels. These units were only really effective in countries with very low humidity.

In 1939 Packard marketed the first mechanical automotive A/C system which worked on a closed cycle. The system used a compressor, condenser, receiver drier and evaporator (fitted inside the boot/trunk) to operate the system. The only system control was a blower switch. Packard marketing campaign included: 'Forget the heat this summer in the only air-conditioned car in the world.' The major problem with the system was that the compressor operated continuously (had no clutch) and had to have the belt removed to disengage the system which was generally during the winter months. Over the period 1940–41 a number of manufacturers made vehicles with A/C systems but these were in small volume and not designed for the masses. It wasn't until after World War II that Cadillac advertised a new feature for the A/C system that located the A/C controls on the rear parcel shelf, which meant that the driver had to climb into the back seat to switch the system off. This was still better than reaching under the bonnet/hood to remove the drive belt. In 1954–55 Nash-Kelvinator introduced air-conditioning for the mass market. It was an A/C unit that was compact and affordable with controls on the dash and an electric clutch.

The design and optimisation of an air-conditioning system

Case study – the air handling system

Experimental approach

In the past, the only way to evaluate a proposed air handling system design was to build a prototype and test it in the laboratory. The air handling components were placed on a test stand, conditioned air was supplied at the inlet and the airflow and temperature distribution at critical locations were measured. This approach takes a considerable amount of time and requires the construction of expensive prototypes. In addition, it provides little or no understanding of why a design performed the way it did. In particular, testing is unable to detect details of recirculating areas, turbulence, temperature stratification and constrictions that adversely impact performance and pressure loss. In addition, the performance of the system usually needs to be evaluated in many different configurations. For example, it sometimes is necessary to evaluate the air handling system in different modes of operation – vent, floor, defrost and mixed – at each of eight different temperature controls.

Modern methods of design

The design process of modern vehicle systems improved with the introduction of Computer Aided Design (CAD), Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM). CAD allows designs to be generated and visually appreciated on a computer. Standard components can be shared among manufacturers and suppliers to ensure that components assemble correctly. Designs can be sent to clients for verification and feedback. Designs can be modified and rechecked within short periods of time in a number of different formats, e.g. an STL file (stereolithography). Complex parts and assemblies can often be manufactured very quickly using rapid prototyping facilities (CAM). CAD also includes the facility to provide virtual testing. This is generally provided using additional modules or add-ins converting CAD to CAE. A number of secondary schools in the UK have the use of Solidworks as a CAD package for their technology departments which include add-in modules like Cosmos Works for Finite Element Analysis and Computational Fluid Dynamics. Finite Element Analysis (FEA) is basically mechanical stress analysis and Computational Fluid Dynamics (CFD) analyses the flow of a fluid like air through or over complex geometry. These additional features are all computer based and use mathematical equations built into the software to predict variables like the stress distribution of a component or assembly (FEA) or the flow of air through an air vent (CFD). All these tests would have originally been carried out manually with continual adjustments being made to a model to optimise it.

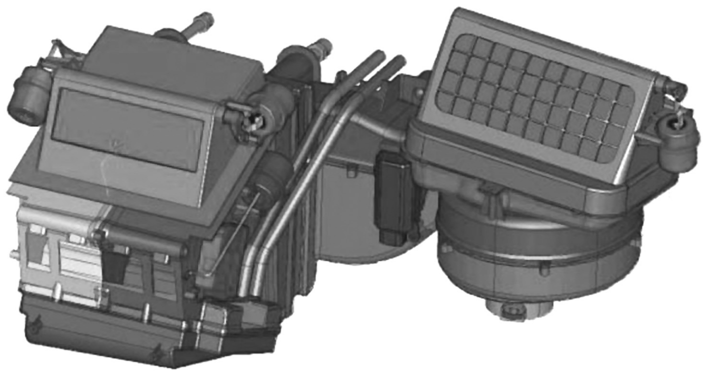

Figure 1.1 Computer generated model designed using CAD (without ducting and vents) (© 2005 Visteon All Rights Reserved)

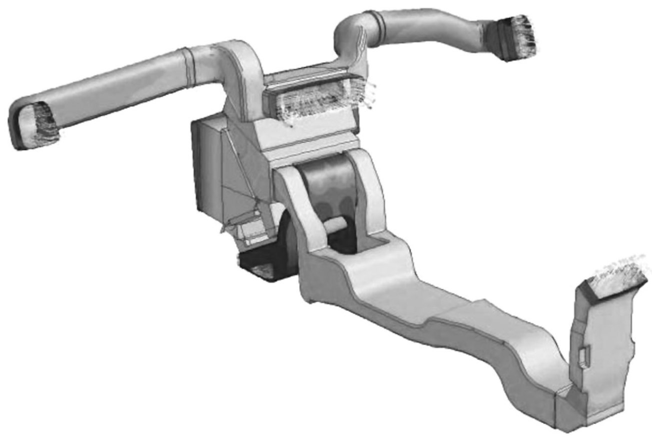

Figure 1.2 Air pressure loss predicted by CFD (© 2005 Visteon All Rights Reserved)

The process

The A/C system begins life as an idea driven by consumer needs or sometimes government legislation. This leads to a specification. The specification will include minimum performance requirements, temperatures, control zones, flow rates etc. This will lead to a number of concept designs. The designs will have a number of computer generated models which will be presented as possible solutions to the original specification. These need to be tested for their performance.

Performance testing using CFD may include fluid velocity (air flow), pressure values and temperature distribution. Using CFD enables the analysis of fluid through very complex geometry and boundary conditions. The geometry typically includes ducts that expand and contract, change from round to square cross-sections, go through complex curves throughout their length, and have many branches and internal walls.

As part of the analysis, a designer may change the geometry of the system or the boundary conditions such as the inlet velocity, flow rate etc. and view the effect on fluid flow patterns.

CFD is an efficient tool for generating parametric studies with the potential of significantly reducing the amount of experimentation required to optimise the performance of a design.

A fan performance curve can be inputted into a model. Without this feature, the user has to guess the flow within the enclosure, calculate the pressure using CFD and see if it matches the

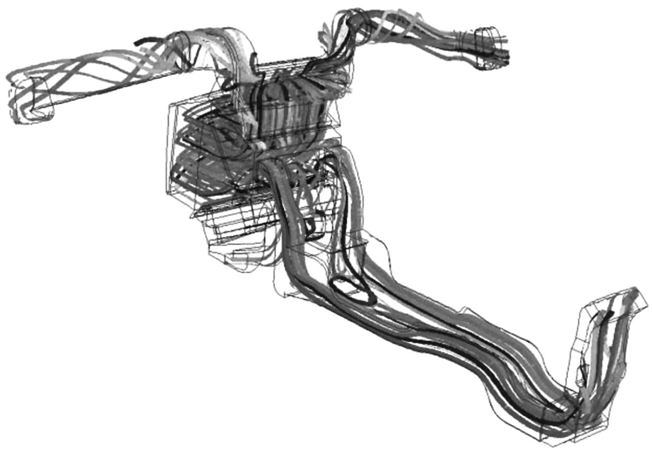

Figure 1.3 Streamlines showing flow field in an air handling system (© 2005 Visteon All Rights Reserved)

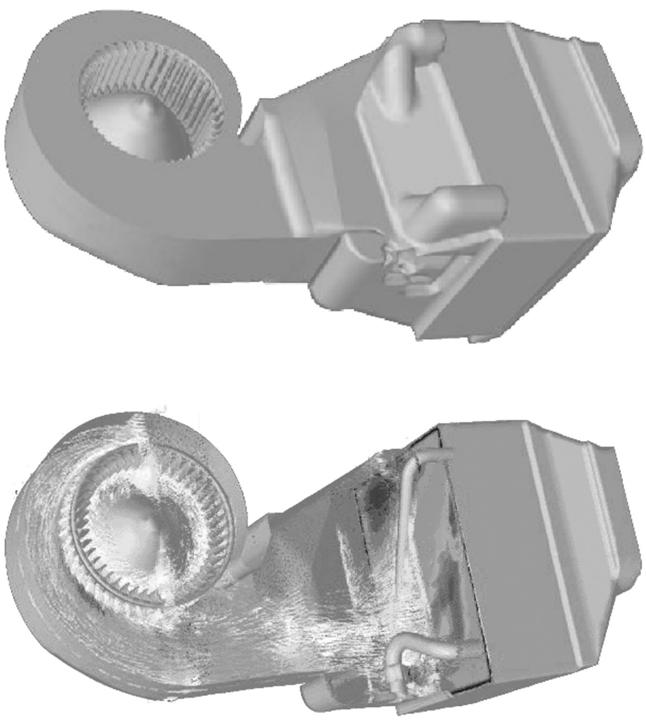

Figure 1.4 Fan flow optimisation (© 2005 Visteon All Rights Reserved)

fan's characteristics. If the pressure doesn't match, then another guess has to be made. Normally, at least three iterations (test runs) are required to make a match.

The software enters the fan curve directly into the model. Each analysis run then interacts with the fan curve to determine the precise operating conditions of the fan as part of the regular

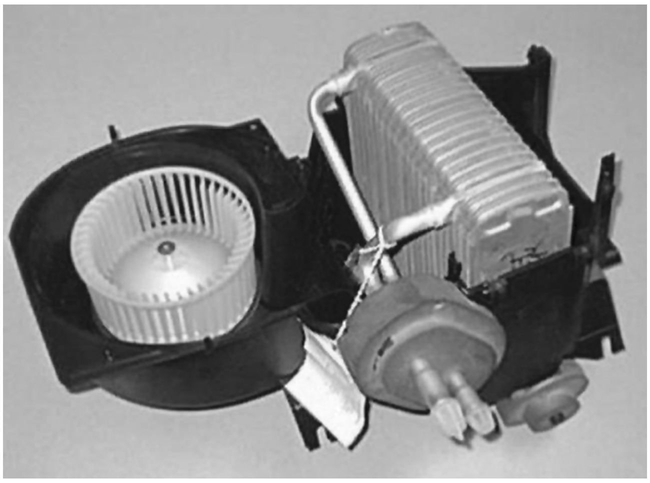

Figure 1.5 Improved fan design
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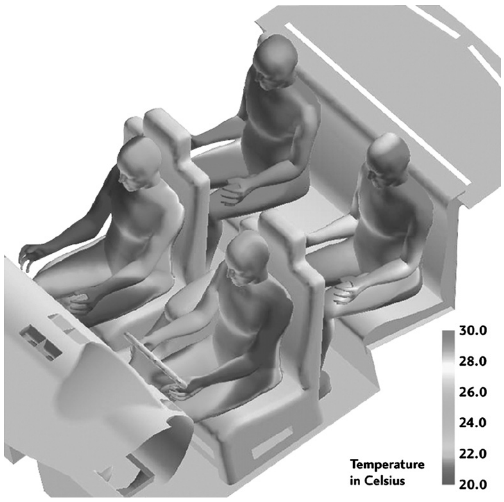

Figure 1.6 Human modelling for temperature distribution
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analysis. Using this technique, engineers can easily determine what type of fan is required to meet air flow requirements within the vehicle, normally 158 cubic feet per minute (75 litres/second) for heating and 300 cubic feet per minute (141.6 litres/second) for cooling.

As a typical example of improvements consider the typical design specification of the HVAC system with respect to the temperature dial on the instrument panel. In other words, moving the dial from position one to position two should have the same impact on temperature as moving from position two to position three. In the past, the linearity of the temperature dial could not be estimated until full vehicle prototypes were constructed. At that point, changes were costly and the testing data provided little or no input on what type of changes were required.

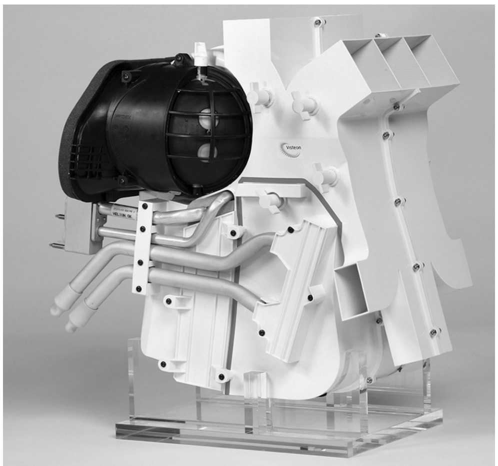

Figure 1.7 Prototype HVAC unit for testing
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Now, engineers can determine the linearity of a proposed design as soon as the solid model has been created in a matter of days. They typically set up a series of analysis runs that evaluate eight different temperature settings at each of the three HVAC system modes. In less than a week, they can determine outlet air temperature at each setting.

Once all CFD modelling is complete the prototypes are made to ensure the physical models operate as predicted by the computer models. The accuracy of simulated and actual system performance can vary up to 10–15%. Generally, lead times are reduced and designs can be evaluated much quicker allowing more time to optimise their working performance.

1.2 Introduction to heating and ventilation

Heating and ventilation in automotive transport is not just a function of temperature control. The safety of occupants to reduce driver fatigue, ensure good visibility and maintain comfort is key to the successful design of such systems. A continual flow of air through the vehicles interior reduces carbon dioxide levels, acts as a demister and prevents the build-up of odours. Carbon dioxide in high concentration can cause a driver to be less responsive. There are recommended ventilation rates which specify the number of times the internal cubic capacity (air space) of the vehicle must be replaced per hour. Included in this calculation are the number of possible occupants and the internal volume of the vehicle. In some countries the performance of a heating and ventilation system is governed by legislation. The heating and ventilation system combined with an air-conditioning system provide a temperature range for occupants to select from. This can be a real challenge due to some extreme weather conditions experienced across the globe. Often auxiliary booster devices are required to provide additional 'heating' or 'cooling' of the interior.

The car heating system

Heat is a form of energy which means it cannot be destroyed. The principle of the heating and ventilation system is to transfer enough heat from one point to another. The heater is a device which heats the air entering or already inside the vehicle (recycled air). The heated air is then directed to a combination of different places via a distribution of air ducts within the vehicle.

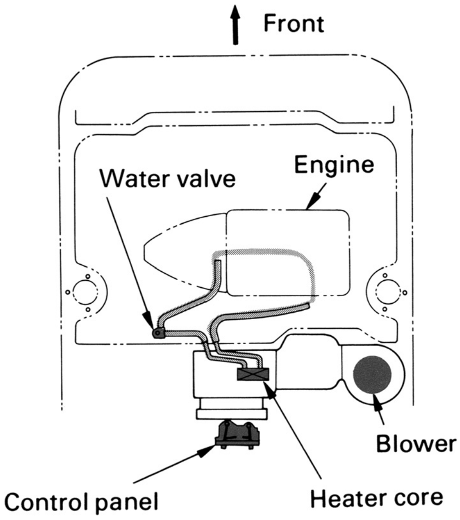


Figure 1.8 Water cooling system
(with the agreement of Toyota (GB) PLC)

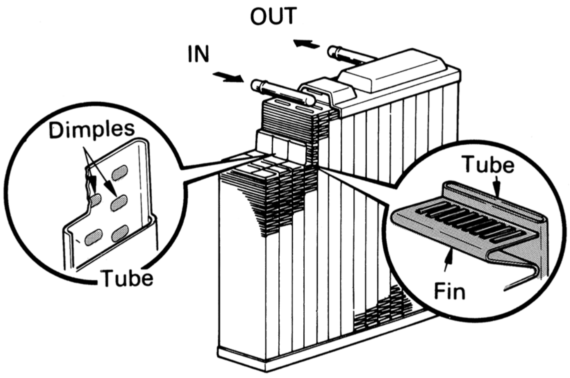


Figure 1.9 Heat exchanger

There are a number of different methods available to heat the air – exhaust heater, heat as a by-product of combustion, electric heater etc. Generally motor vehicles use heat from combustion which is transferred through water or air depending on whether the engine is water or air cooled. If the vehicle is air cooled then a system of shrouds is used to direct the heat from the external surface of the engine or exhaust or in some cases from the lubrication system towards the inside of the vehicle.

Water-cooled engines

The engine has a water cooling system which is used to maintain engine temperature by transferring combustion heat (as a by-product of the combustion process) away from the combustion chamber. The heated coolant is then carried from the combustion chamber through pipes to a heat exchanger.

The heater exchanger (heater matrix)

The heat exchanger, often called the matrix, is situated inside the vehicle housed within the heater assembly. It is designed to have a large surface area enabling air to pass over the surface of its fins. Fresh or recycled air (air from inside the vehicle) is directed under force over the surface of the heater core and then distributed via air and panel vents into the vehicle's interior. The heater core is made up of tubes and fins which are made from aluminium alloy and have aluminium or plastic tanks attached to the core with inlet and outlet ports.

Heat control

Heat control is determined by the occupants of the vehicle. This is done by selecting the required interior temperature which the occupants require via a control panel. The control panel will either control components to allow more or less water to enter the heat exchanger or allow more or less air to flow over its external surface. These two systems used to control the heater's thermal output are referred to as:

1. Water flow type.
2. Air mix type.

Water flow type

This system controls the amount of coolant flowing from the engine cooling system to the heat exchanger using a control valve. The control valve (Figure 1.11) varies the flow of coolant going inside the heat exchanger which in turn varies the temperature of the heater core. Regulation in such a system can be difficult especially with the coolant flow and temperature being dependent upon engine speed and load. The system does not respond immediately to

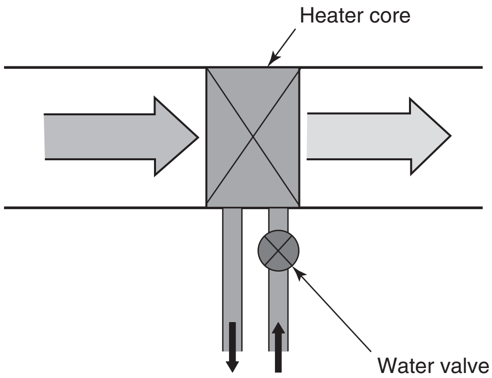


Figure 1.10 Heat controlled by a water valve (with the agreement of Toyota (GB) PLC)

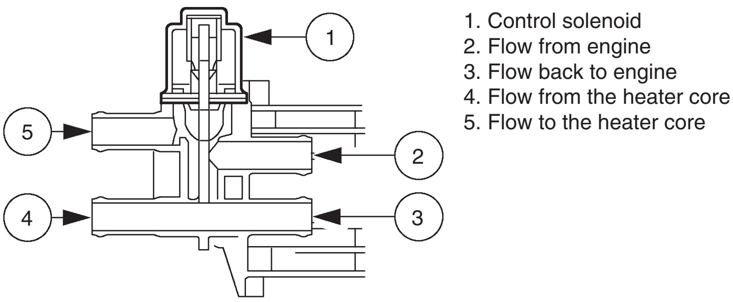


Figure 1.11 A solenoid operated water control valve (reproduced with the kind permission of Ford Motor Company Limited)

change, for example if a lower temperature is required to the interior then the control valve will restrict the flow of coolant to the heater core. To achieve the reduced temperature the heater core must lose the heat required to cool to the new selected temperature, thus giving off heat. A benefit of regulating the heater core is that it allows the whole volume of air to flow through the heater core itself, improving heating performance.

Air mix type

This system controls the volume of air allowed to flow over the surface of the heat exchanger using an air mix/blend control door. The internal door directs air over or bypassing the heater core depending on its position. The position is determined by the occupants who select a temperature range from hot to cold. If a mid-range temperature is selected then the quantity of air will flow over the heater core and a quantity will bypass the heater core. This air will then mix later in a mixing chamber to reach the final required temperature before leaving the heater assembly. The air mix control doors are generally operated by Bowden cable, vacuum or electronic servo. The negative aspect of such a design is that the use of a mixing chamber means that the heater assembly tends to be larger for the air mix type than the coolant controlled type. When not in use heat can radiate from the heater core warming natural air flow which is transferred to the cabin space although this can be overcome by using a shut-off solenoid to stop the flow of coolant when maximum cooling effect is required. Positive aspects include quick response to changes in temperature and more accurate control of temperature variations.

Air distribution through the interior of the vehicle

A ventilator is a device used to direct air through the inside of a vehicle. There are generally two types of ventilator used on a vehicle:

1. Natural flow ventilator.
2. Forced flow ventilator (blower).

Natural flow ventilator

This is created by air pressure outside of the vehicle caused by the forward motion of the vehicle. As the vehicle moves in a forward direction positive and negative pressure is created on the vehicle's surface due to its aerodynamic shape. Areas where positive pressure is created are ideal places for air vents which allow air to enter the vehicle, travel through the interior and then exit the vehicle via a vent often positioned in a negative pressure region. The air intake is positioned

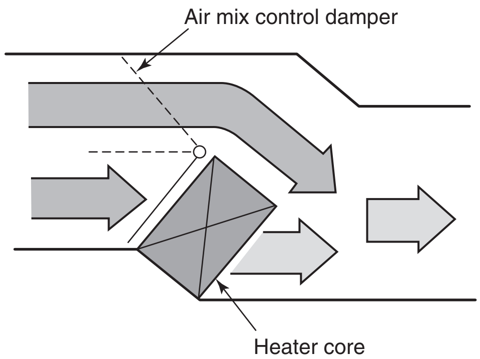


Figure 1.12 Heat controlled by an air mix control damper (with the agreement of Toyota (GB) PLC)

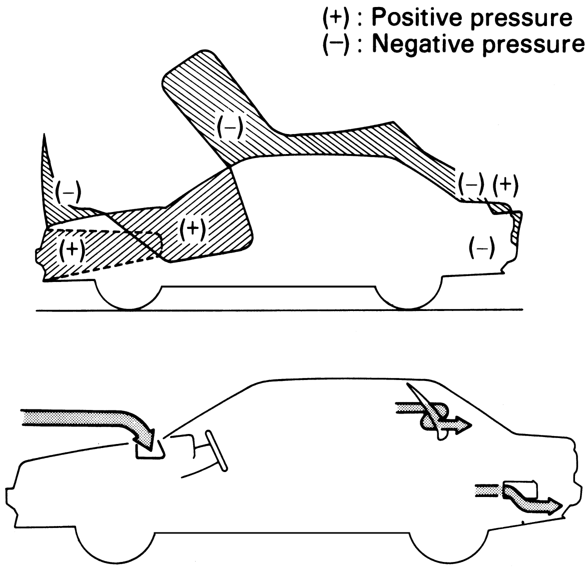


Figure 1.13 Positive and negative pressure across the surface of the vehicle (with the agreement of Toyota (GB) PLC)

at the bottom of the windscreen where static pressure is high so air under pressure can flow into the vehicle. There are a number of downsides to this position:

1. The engine compartment must be adequately sealed so no dissatisfying smells find there way into the interior of the vehicle.
2. Air flow is proportionate to vehicle speed causing lack of flow at low speeds and possible excessive noise and draughts at high speed.

This is generally reduced by only allowing a small pressure differential between the intake and exhaust of air and adequate fan assistance. Air exhausts through outlets, which are mostly located in a rear pillar hidden behind a trim panel or behind the rear bumper.

Air inlet and outlets

In Figure 1.14a to separate dirt particles and water from the air taken into the passenger compartment, the fresh air is fed through a cowl panel grille and pollen filter housing (2). This often houses air filtration systems like pollen filters (1). The pollen filter is able to clean the fresh air from smaller particles, such as dust and pollen which are able to get through the cowl panel grille.

The air outlets are arrangements of rubber flaps, mostly hidden behind the rear bumper or behind a trim panel on the rear pillar. Because the pressure in the passenger compartment is created by the blower motor and natural air flow, the air outlets open and air exchange can take place. If there is no air flow through the vehicle interior, the flaps close to prevent exhaust fumes from entering. If vehicle ventilation is unsatisfactory, check the flaps for freedom of movement.

In case of exhaust fumes reaching the luggage compartment, check the closing function of the flaps and their tightness.

Forced air flow

In forced air ventilation systems an electric fan is fitted inside the vehicle. Fans are generally used when vehicle speeds are low or comfort demands are high (demisting, heating and cooling).

(a) (b)

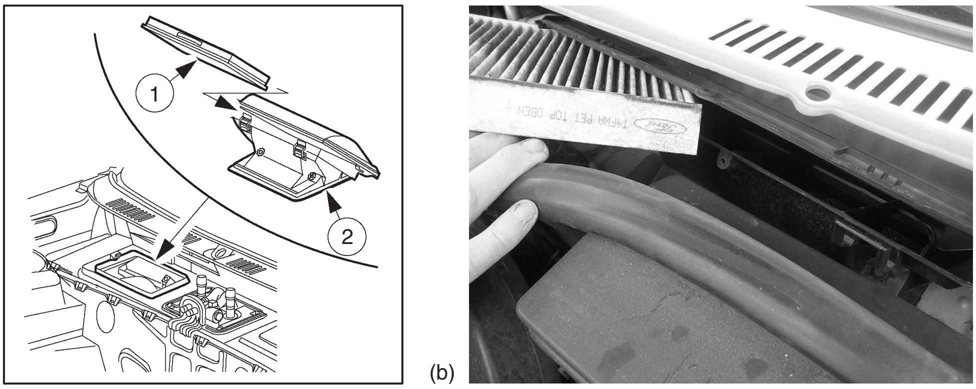


Figure 1.14 (a) Fresh air inlet; (b) Fresh air inlet Ford Fiesta (reproduced with the kind permission of Ford Motor Company Limited)

The blower fan can force air over the heater core allowing the heat to be transferred to the air which is distributed around the vehicle. Intake and outlet vents to the interior are generally located in the same position as the natural flow ventilator. Figure 1.8 shows the position of the fan (blower) within the system.

Fan design

All fans are driven by an electric motor. The motor can rotate at varying speeds depending on the current supplied to it (Chapter 3). The fan allows the air flow to be adjusted according to the requirements of the occupants. Fans are generally divided into axial and centrifugal flow types. In axial type fans the air is drawn in and forced out parallel to the rotating axis. In the centrifugal type the air is blown in on the rotating axis and forced out perpendicular to the rotating axis (the direction of centrifugal force). The shape of the vanes of the fans are often profiled to maximise flow and volume and minimise size and noise. The blower is a dominant low-frequency source of noise, while at higher frequencies, additional air flow noise sources exist. These include high shear regions within the ducting, separation of flow due to flow obstructions, and the exit flow from air vents. Flow optimisation can be achieved using CFD (Computational Fluid Dynamics), which allows an engineer to analyse flow patterns and pressure regions within the system and make adjustments on the size, shape and position of components in efforts to make the system as aerodynamically efficient and quite as possible. Other efforts included noise isolation through the use of padding or positioning sources outside of the interior.

Air filtration

Pollen filter

The filter is located in the heater assembly housing before the heat exchanger (Figure 1.15a and b). Fibres in the filter prevent large particulates from entering the system and trap the really small ones, the filter is electrostatically charged. Due to this electrostatic charge, the filter attracts particles like a magnet attracts iron filings. Besides removing visible particles, the filter also removes pollen, spores and different types of dust etc. from the cabin air.

Carbon filter and germicidal lamp

An active carbon combination filter and/or a germicidal lamp are generally fitted as an option in place of the pollen filter. The active carbon combination filter has the same advantages as the

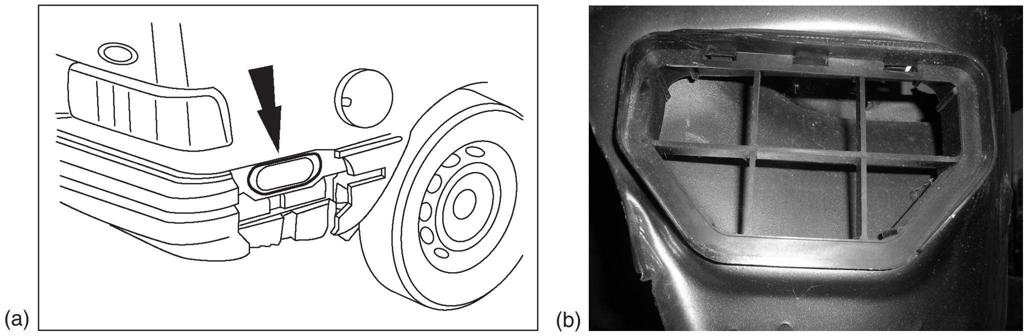


Figure 1.15 (a) Rear air flap. (b) Rear air flap Ford Fiesta (rubber flap removed) (reproduced with the kind permission of Ford Motor Company Limited

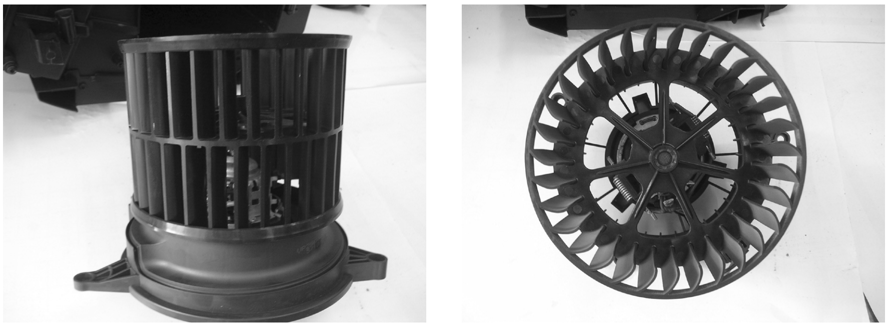


Figure 1.16 Centrifugal type fan assembly

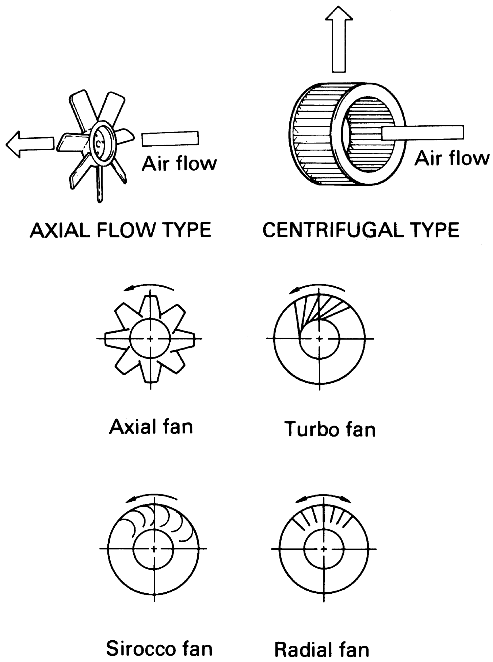


Figure 1.17 Axial type fan assembly

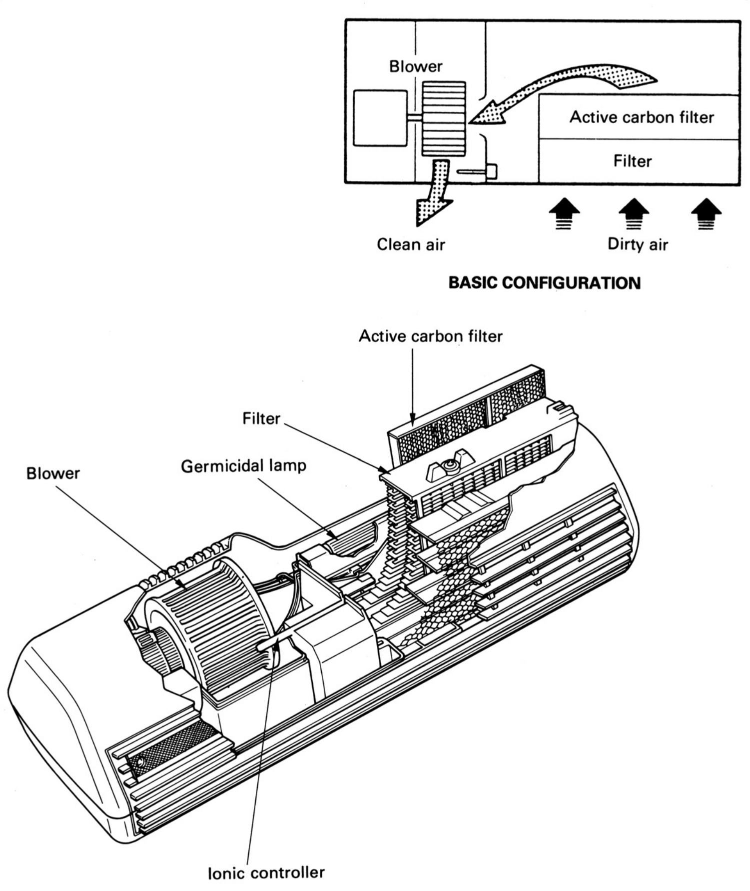


Figure 1.18 Air filtration system with pollen, carbon filter and germicidal lamp (with the agreement of Toyota (GB) PLC)

pollen filter plus an effective active carbon layer. The active carbon layer neutralises unpleasant odours and keeps the air free of ozone. It also reduces diesel exhaust fumes from entering the interior of the vehicle. A germicidal lamp is used in air-conditioning systems to kill any bacteria which enters or forms within the air filtration system. This also stops odours in the system through the build-up of bacteria (see section 5.4).

Photo catalytic filter

Photo catalytic filters destroy pollutant gases and micro-organisms entering the vehicle. In less than five minutes the entire cabin air can be purified.

Benefits:

1. Continuous protection against potentially harmful external/internal pollutants and from discomforting odours.
2. Alleviation for allergy sufferers – micro-organisms causing allergies are destroyed.
3. Extended service life of filters – 2000 hours, equivalent to approximately five years' average vehicle use.
4. Complete destruction of pollutants compared to today's carbon filters.

(a) (b)

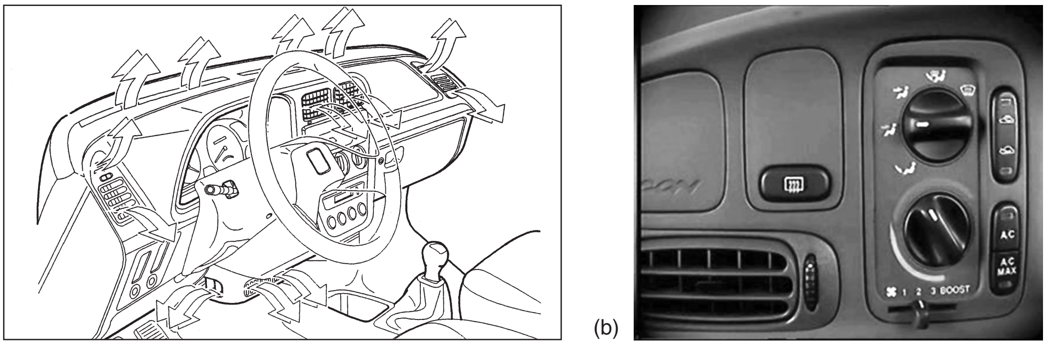


Figure 1.19 (a) Air distribution showing panel, face and floor vents (b) Manual control panel (reproduced with permission of Peugeot)

Photo catalytic oxidation converts toxic compounds like carbon monoxide and nitrous oxide into benign constituents such as carbon dioxide and water without wearing out or losing its effectiveness. When light strikes titanium oxide, hydrogen peroxide (H_2O_2) and hydroxyl radicals (OH) are formed. These two substances possess powerful oxidising properties and through mutual interaction are able to decompose odorous substances into odourless carbon dioxide and water. A powerful oxidative also removes bacteria and deactivates viruses.

Air quality sensing

An Air Quality Sensor (AQS) can be located in the main air inlet duct of the HVAC system. When a threshold for carbon monoxide or nitrogen dioxide is reached, the AQS communicates to the HVAC system to initiate the air recirculation mode. For more information see section 3.2.

Directing air flow and controlling temperature range can be manually selected by the occupants or electronically controlled via a control module. The heating system is designed to offer a temperature range. Research into a comfort zone for passengers exists but is subjective due to different nationalities that are acclimatised by the weather on their continents. The basic heating and ventilation system control panel contains a temperature control knob and a number of air distribution options.

Air distribution unit

The air distribution unit is generally located under the instrument panel of the vehicle. Inside the air distribution unit there is a system of ducts and mixing/directing doors. In addition the unit houses the blower motor, the heater core and for vehicles with an air-conditioning system, the evaporator. The filtered incoming air from the intake panel grille is induced by the blower motor and is forced under centrifugal force to the air distribution unit. The air coming from the blower is directed to the different air ducts through the moving doors in the air distribution unit. The temperature is regulated by mixing warm and cold air. The air is then directed to different air outlets/air nozzles and panel vents. There are basically two ways for the ventilation system to take in air: fresh air from the outside and recirculated air from the interior. Therefore the air distribution unit has two air inlets which are alternately closed by a door. Operating in recirculation mode allows to keep away unpleasant outside smells from the inside and it also improves the cooling output of the air-conditioning system. When recirculation mode is switched on for a longer period of time, the humidity level inside the vehicle will increase because of the moisture content of the breath of the passengers. This can lead to fogging on the windows. Switching to fresh air mode with air-conditioning system reduces the humidity of the inside of the vehicle.

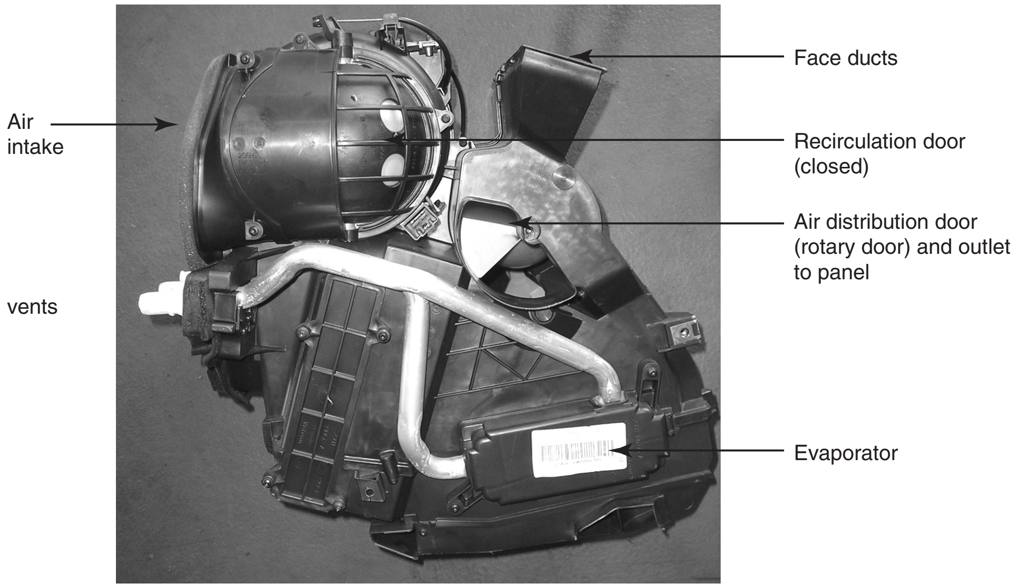
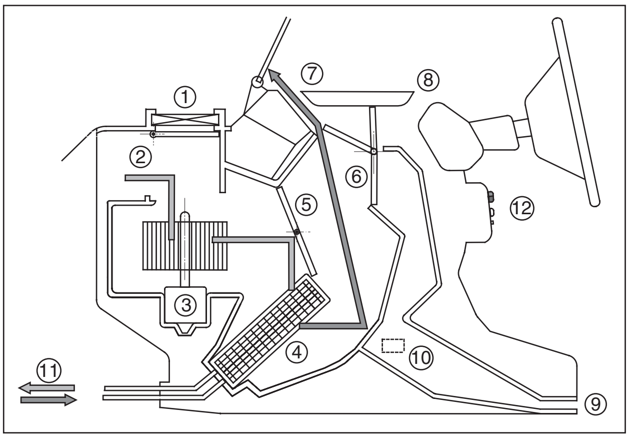


Figure 1.20 Heater assembly



1. Air filtration
2. Air recirculation door
3. Blower motor and centrifugal fan
4. Heat exchanger
5. Temperature blend door
6. Air distribution door
7. Panel vent (not adjustable)
8. Face/head vent (adjustable)
9. Panel vent – rear passengers' foot well
10. Ducting to passenger foot well
11. Flow of coolant
12. Control panel

Figure 1.21 Air recirculation

Simplified view of system components

Figure 1.21 shows the air intake door (recirculation door) is closed so no external air will enter the vehicle except through a port which feeds the blower motor from the interior. The blower is operating so air inside the vehicle will be recirculating around the vehicle's interior. The heat exchanger will still heat the air as required as long as there is a difference in temperature and the occupants have selected so via the control panel, which will vary the position of the temperature blend door (2). While the air is recirculating there is a danger that water vapour will condense on the inside the vehicle's windscreen. This is affected by the following:

- external air temperature;
- interior temperature;
- number of occupants;
- relative humidity of the air inside the vehicle.

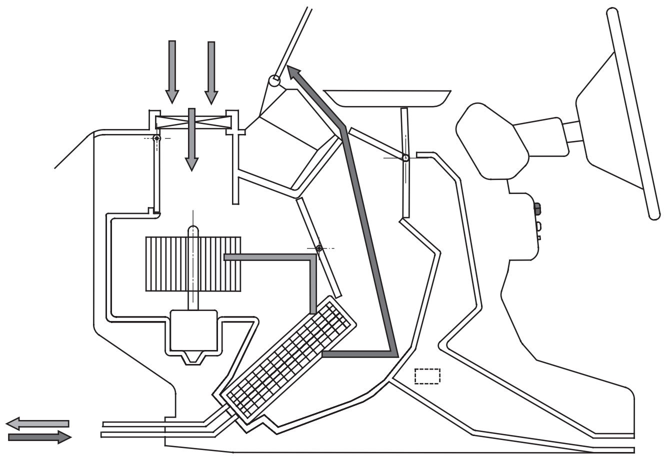


Figure 1.22 Demisting position

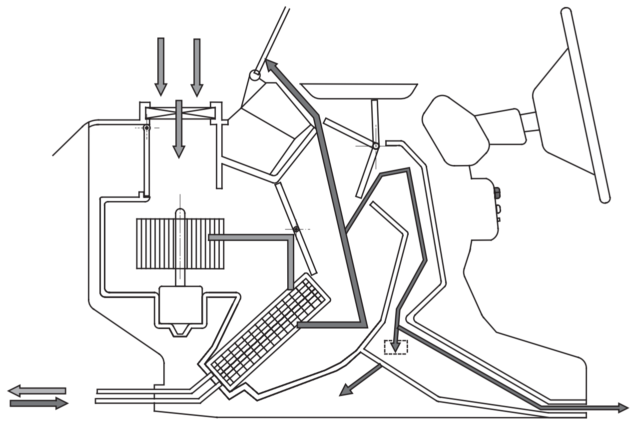


Figure 1.23 Demisting and heating the occupants

If this occurs then air recirculation must stop and external air must enter the vehicle through the air intake door. Recirculation of air is often selected when driving in polluted areas, e.g. heavy traffic.

In the demisting position (Figure 1.22) the air from outside is moved under force from the blower motor to the temperature blend door which is fully closed. This forces the total volume of air to flow through the heater core where it will be heated and then directed by the top distribution door towards the windscreen and side windows. Note that no air is directed towards the occupants. This allows the maximum volume of air to flow to the windscreen to aid the demisting process. This is done through the evaporation of the condensed water droplets on the screen (see section 1.3).

In Figure 1.23 the air intake door is fully open allowing external air to flow through to the blower. The blower forces air towards the temperature blend door which is fully closed forcing all the air to flow through the heater core. All the air flows through the heater core and is then directed to the top distribution door where a portion is directed towards the windscreen and side windows and the rest is directed to the foot vents which includes passengers in the rear of the vehicle.

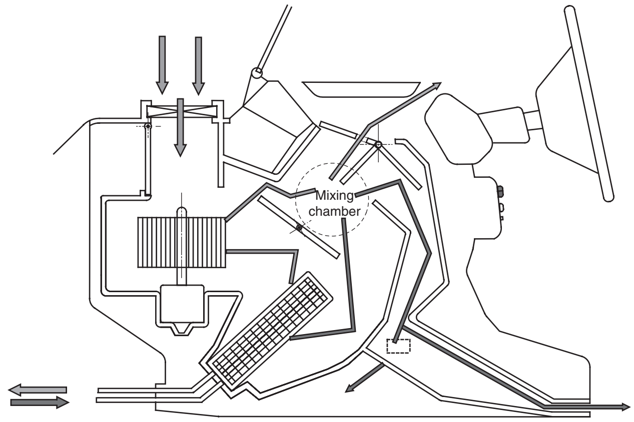


Figure 1.24 Heat directed to occupants' feet and face vents

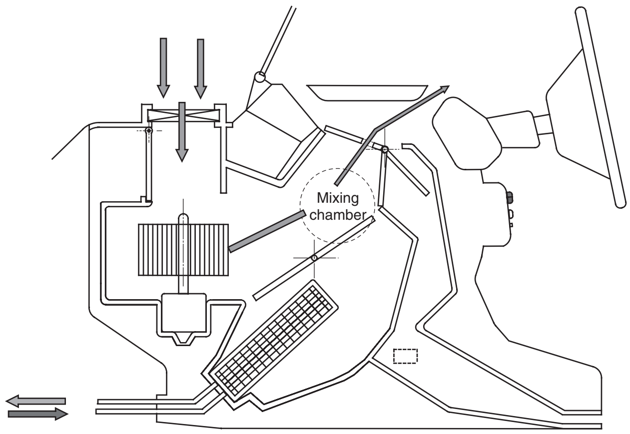
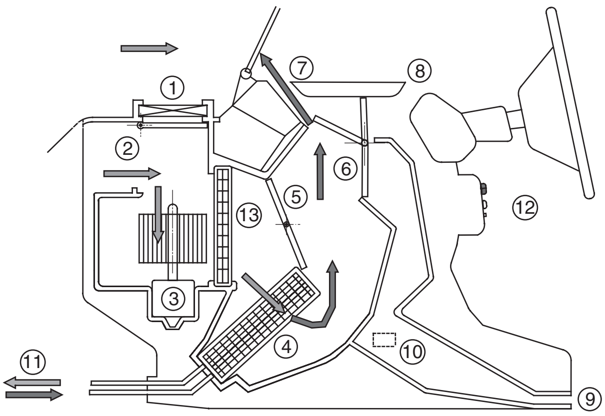


Figure 1.25 Air flow directed to face vents

The air intake door is fully open allowing air to flow through to the blower. The blower forces air towards the temperature blend door. The blend door directs a volume of air towards the heater core and the rest towards the distribution door allowing air to flow to the face vents. The air going through the heater core is then directed towards the back of the blend door and then the distribution door, where it is distributed by the feet vents (Figure 1.24).

There will be a temperature difference between the face vent and feet vent of approximately 7°C. This is due to humans feeling comfortable with their feet being warmer than their head in cold conditions.

The air intake is fully open to allow air to flow through the blower. The blower forces air towards the temperature blend door and depending on its position it will direct air straight to the top distribution door and the face vents or it will direct a portion of the air towards the heater core to raise the temperature of the interior and improve the comfort levels of the occupants (Figure 1.25). The interior temperature is generally controlled by the occupants via the control panel. This selection offers the occupants fresh outside air straight to the head which is beneficial in hot weather conditions removing heat from the occupants by convection. This increases the occupants' comfort, especially if perspiring, allowing the latent heat of evaporation to remove sweat producing rapid cooling, relative humidity permitting (see section 1.3).



1. Air filtration
2. Air recirculation door
3. Blower motor and centrifugal fan
4. Heat exchanger
5. Temperature blend door
6. Air distribution door
7. Panel vent (not adjustable)
8. Face/Head vent (adjustable)
9. Panel vent – rear passengers' foot well
10. Ducting to passenger foot well
11. Flow of coolant
12. Control panel
13. Evaporator (models with A/C)

Figure 1.26 System with evaporator fitted

System components with A/C (including evaporator)

Figure 1.26 illustrates the position of the evaporator in the heating and ventilation system. All air passes through the evaporator irrespective of whether the system is operating. When the A/C system is running the evaporator temperature is approximately 2–6°C (°F). This causes the temperature of the air to reduce and moisture in the air to condense producing water droplets on the evaporator's surface. This reduces the moisture content (dehumidifying) of the air and also helps to remove dirt particles (purifying) suspended in the air stream. The water covers the surface of the evaporator trapping dirt particles and eventually dripping off the surface on to a drain tray which directs the water to the outside of the vehicle.

Note – if the drain pipe becomes blocked then water will enter the inside of the vehicle.

Air vents

Air vents must be ergonomically designed to avoid draughts. Directional air vents generally have three adjustments, up and down, left and right and open and closed. Circular vents are also used which are free to rotate within a given circumference. The vents are generally used for face/head heating. Panel air vents are fixed and cannot be adjusted. These are generally used for windscreen and side screen demisting and floor heating.

Air diffuser system

The soft air diffusion system has been specifically designed to produce an evenly distributed blanket of air that provides all vehicle occupants with the same high level of climatic comfort.

A range of diffuser systems are used within commercial heating and ventilation systems. They are now being implemented within automotive climate controlled systems. There are a range of diffuser types depending on the required air flow characteristics:

- Linear diffusers provide continuous air flow across the length of an outlet. Air flow is quiet and comfort increases while reducing drafts.
- Mini-flow is used when quiet delivery and a low velocity of air is required.
- Gentle-flow air jets with diameters ranging from 1/4″ to 1/2″ diffuse more quickly.
- Super-flow air jets with diameters ranging from 1″ to 6″ can be used for a wide variety of applications. The long throw of the air jets effectively propel air to greater distances.

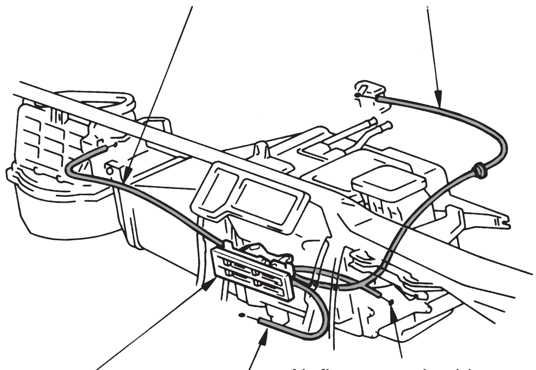


Figure 1.27 Bowden cable used for air inlet, temperature blend and water flow control (with the agreement of Toyota (GB) PLC)

Benefits of using diffusers

- Alleviates discomfort – eliminates draughts from A/C system experienced by occupants of front seats.
- Improves climatic comfort for all occupants – air is distributed evenly throughout the cabin and is particularly beneficial to back seat passengers.

Air door actuators

The doors are opened and closed by Bowden cables, pneumatic control motors or electrical control motors. Manually regulated systems use Bowden cables in most cases. Automatic and semi-automatic systems require control motors. These can be operated electrically or pneumatically. The pneumatic control motors are also actuated electrically by the solenoid valve in the vacuum lines.

Bowden cable

Doors can be operated mechanically by Bowden cables. The rotation or sliding of a control switch provides movement which is transmitted by cable to the doors.

Pneumatic control

Pneumatic control actuators consist of a diaphragm unit attached to an actuator rod. The diaphragm has a spring acting on its surface holding it in position. To move the diaphragm the spring pressure must be overcome. This is achieved by applying a vacuum via the vacuum connection (1). The vacuum is supplied by the engine inlet manifold often via the brake vacuum servo connection (petrol engine) or brake vacuum pump (diesel engine). The vacuum creates a pressure above the diaphragm which is lower than atmospheric pressure. The diaphragm housing has a hole in its base allowing atmospheric pressure to act on the bottom surface of the diaphragm thus the force of atmospheric pressure is used to overcome the spring tension. The rate of movement is dependent on the spring tension and the difference in pressure between the upper (vacuum) and lower (atmospheric) sections of the diaphragm. As the diaphragm moves the actuator rod

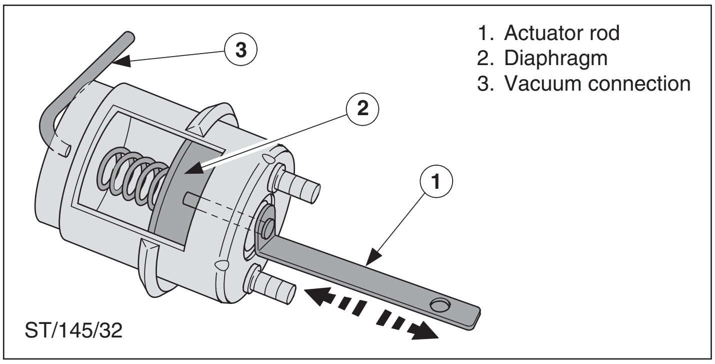


Figure 1.28 Recirculation air actuator vacuum operated (reproduced with the kind permission of Ford Motor Company Limited)

moves as well. The actuator rod is attached to a door inside the HVAC unit. The door opens or closes airways for recirculation (Figure 1.28). Pneumatic control actuators generally have two positions – open and closed. They can be controlled by varying the vacuum applied using a variable orifice or by applying two connections of different diameter to apply different pressures. If variable control is required it is easier to employ an electric motor.

A vacuum accumulator is generally employed to control the fluctuating pressure applied to the diaphragm unit through the use of a non-return valve. A solenoid is also fitted to the system to control fluctuating pressure when vacuum is applied. The valve can be operated manually by means of switches or automatically by a control module.

This system has a number of drawbacks:

1. The vacuum is taken from the inlet manifold and uses critical energy otherwise used to aid combustion.
2. If a leak is present in the system then combustion efficiency will be greatly reduced and pollutants from exhaust emissions will increase.
3. The unit can only fully open a flap or fully close a flap if there is no position between these points.

These units have generally been replaced with electric motors giving greater control.

Electronic control

Electrical control motors are used for fine adjustment of blend/distribution doors. These motors are usually used for operating the temperature blend door and air distribution door, as this door has to be moved proportionally. Systems with electronic temperature control often have an integrated potentiometer in the control motor, which gives feedback to the control module about the position of the door (for a full explanation see Chapter 3).

Classification of heating and ventilation systems by zone

A zone is an area of the internal space of the vehicle that can be cooled or heated to a specific temperature. For example, a driver may feel hot due to their clothing and require cooling and a passenger may feel cold and require heating. Both occupants have a set of controls to adjust the temperature and ventilation rate of their personal space. Systems that have more than one zone are generally electronically controlled. Heating and ventilation alone can be split for

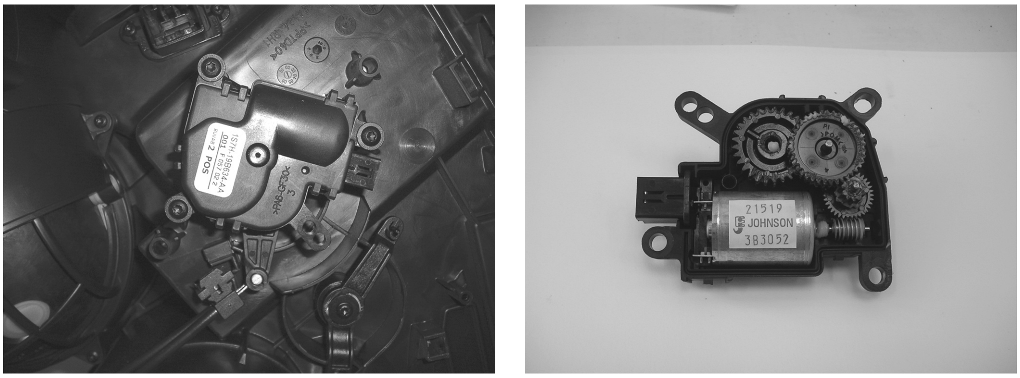


Figure 1.29 Electrical control motor and reduction gear

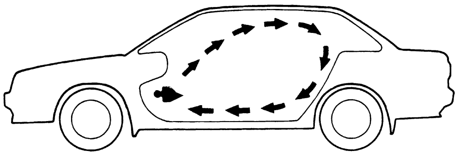


Figure 1.30 Dashboard installed HVAC system (with the agreement of Toyota (GB) PLC)

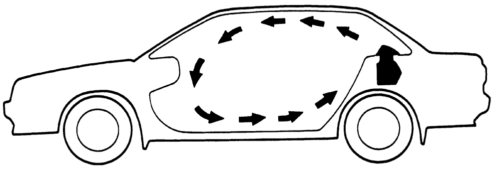


Figure 1.31 Boot installed single zone HVAC system (with the agreement of Toyota (GB) PLC)

zone control but generally if systems have this facility they include heating, ventilation and air-conditioning (HVAC).

Dash HVAC

Installed under the dashboard with one single zone which is the interior space. The dashboard type has the benefit of forcing cold air directly to the occupants enabling the cooling and heating effect to be felt to a much greater degree than the system's capacity to cool or heat the entire space. Example – the output at the air vent on an HVAC system might be 2°C which can be blown directly on to the occupant's head for immediate cooling. The interior space will only cool to approximately 22°C.

Boot HVAC

Installed in the boot which has a large space available for the heating and cooling units. The outlets are positioned at the back of the rear seat. Negative aspects of this design include loss of boot space and cool air streams flowing from the rear of the vehicle.

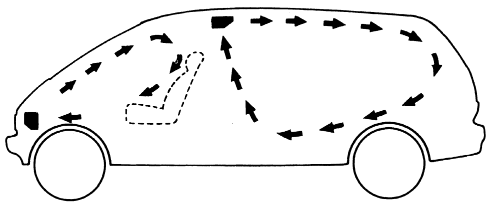


Figure 1.32 Dual zone dashboard installed HVAC system (with the agreement of Toyota (GB) PLC)

Dual HVAC

Generally installed at the front of the vehicle under the dashboard and extended to the rear. Dual systems can include up to three zones, driver, front passenger and the rear passengers. All zones have a set of HVAC controls to select the desired level of comfort. This system is common on high specification vehicles and MPVs (Multi Passenger Vehicles) – vehicles with a high number of passenger capacities.

Booster heater systems

Booster heating systems are generally used for the following reasons:

1. Large interior cabin space.
2. Efficient engine combustion with low heat output, additional heat input required.
3. Large interior space (MPV – Multiple Passenger Vehicle).
4. Vehicles operate in extreme weather conditions.

The benefits of such a system are as follows:

1. Improved visibility due to demist.
2. Shorter cold start period improving catalytic converter efficiency and less engine wear.
3. Improved passenger comfort.

PTC heaters

Booster heaters can be as simple as an additional water pump fitted to accurately control/boost coolant through the heat exchanger fitted inside the vehicle to improve heating capacity, or a separate unit which can provide additional heat input to the coolant or air distribution by burning fuel (fuel heaters) or electricity (PTC – Positive Temperature Coefficient – heaters). Booster heaters should not be confused with dual heating and air-conditioning systems. Dual systems are extensions of the same system and provide heating and cooling control within designated zones inside a vehicle.

The PTC heater unit has an element mounted on a ceramic base and installed in the heater casing. It directly heats up the air flow entering the passenger compartment.

The key characteristics of a PTC additional heater are:

- rapid heating after starting the vehicle;
- light and compact design;
- the unit cannot overheat;
- maintenance free.

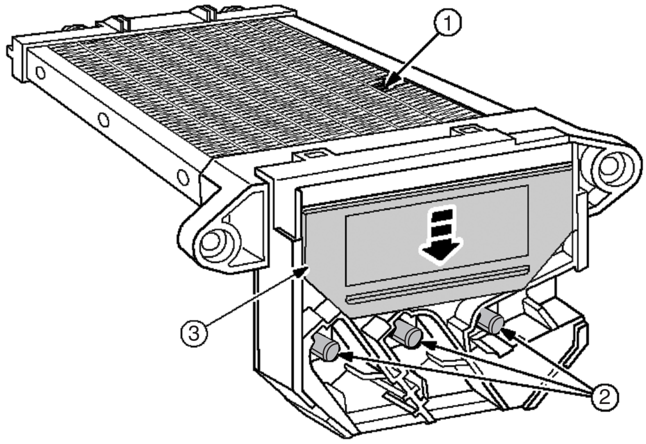


Figure 1.33 PTC heater unit
(reproduced with the kind permission of Ford Motor Company Limited)

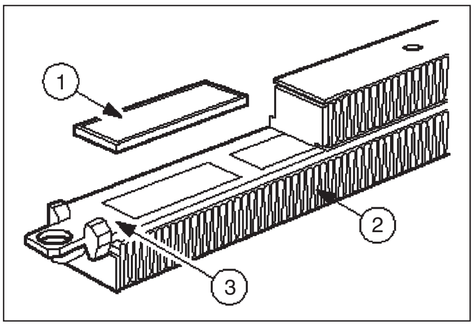
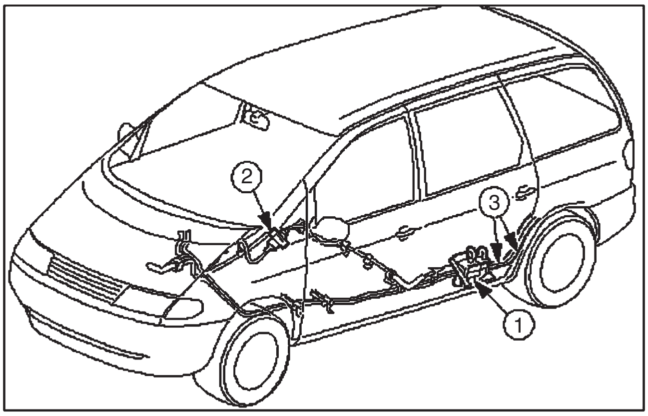


Figure 1.34 Heating element
(reproduced with the kind permission of Ford Motor Company Limited)

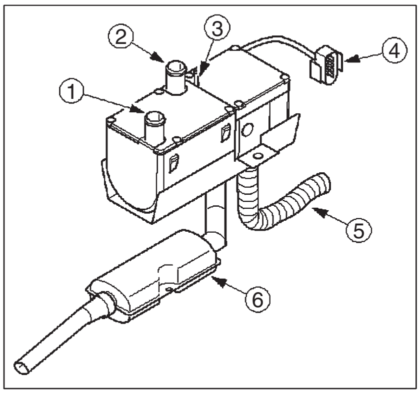
The PTC heater element consists of small metallised ceramic plates, which are layered alternately along the unit core (1), see Figure 1.33 with aluminium radiator elements. These layers are held together by spring elements in a frame. The aluminium elements provide the electrical contacts. They also transfer heat to the passing heater air flow. In order to prevent electrical short circuits due to metal foreign bodies, a heat-resistant plastic mesh with an aperture of 0.8 mm is located on the heater element. The heater element is divided into separate heating circuits with a ratio of one third to two thirds so that the heating power can be adapted to suit different requirements.

PTC heater elements act as a positive temperature coefficient resistor. This means that its resistance value is relatively small at low temperatures and increases with higher temperatures. A high current flows initially when a voltage is applied to the cold PTC element, as a result of which it heats up. As the temperature rises, so does the resistance. This results in a reduced current draw. The time taken to stabilise the current is approximately 20 seconds. The temperature of the additional heater depends on the rate of heat transfer to the surrounding area. If the rate of heat transfer is good, for example, a cold low humidity condition will have a greater temperature difference and allow for a greater rate of heat transfer, therefore the resistance will remain low. Once the air has warmed and the heat transfer rate reduces the PTC unit will start to increase in temperature due to the inability to give up heat. This will cause the



1. Heater unit
2. Fuel metering unit
3. Coolant hoses to rear heat exchanger

Figure 1.35 Diesel heating booster system location
(reproduced with the kind permission of Ford Motor Company Limited)



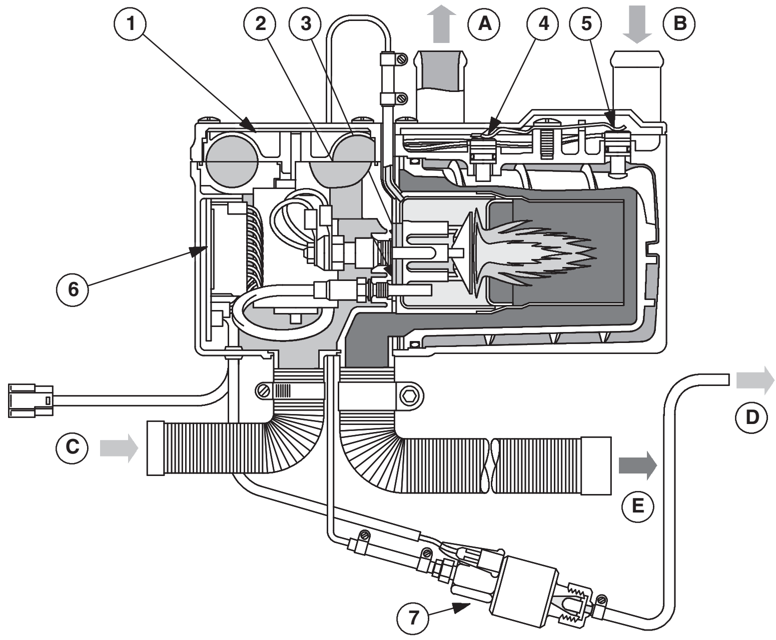
1. Coolant inlet from the engine cooling system
2. Coolant outlet to rear heat exchanger
3. Fuel feed from metering unit
4. Electrical connection
5. Air intake hose
6. Exhaust with built-in damper

Figure 1.36 Booster unit
(reproduced with the kind permission of Ford Motor Company Limited)

resistance on the unit to increase and thus reduce the current flow. The reduced current flow maintains or reduces the temperature. If the opposite occurs and the heater manages to give up heat to the surrounding air then the unit will cool and the resistance will reduce. This will increase current flow through the unit and increase the unit's temperature. As a result of these specific resistance characteristics, it is not possible for the PTC element to overheat. The maximum surface temperature is around 165°C.

The unit is only operated at low ambient temperatures (<15°C, supplied by air temperature sensor) and when insufficient heat can be supplied via the coolant-based heating system (<73°C, supplied by coolant temperature sensor) and low alternator (generator) loadings. The PTC heater consumes a great deal of current so it can only be operated when the engine is running and its operation is phased. Phased operation means that the unit is treated like a three bar electric heater. One bar at a time is switched on so the load on the alternator (generator) is progressive and not sudden. The load will also affect the idle speed and emissions.

The heating power is around 1 kW when fully operating. This places additional loading on the vehicle electrical system. Vehicles with PTC additional heaters are fitted with a more powerful generator.



1. Combustion blower
2. Flame sensor
3. Glow plug
4. Temperature sensor
5. Overheating sensor
6. Control module
7. Metering pump

A. Coolant outlet
B. Coolant inlet
C. Fresh air supply
D. Fuel return line
E. Exhaust

Figure 1.37 Booster heater operation
(reproduced with the kind permission of Ford Motor Company Limited)

Diesel fuel booster system

If a vehicle cannot provide adequate heated coolant to a heat exchanger then it may use a fuel booster to provide the additional heat input. There are a number of manufacturers using such a system due to the ultra efficient diesel combustion system and the large interior space that requires heating. This is often between 1 and 3 kW. At maximum output the fuel penalty is 0.38 litres/hour and the operating temperature is between −40 and +80°C. Once above 80°C the unit shuts down. Such units can provide a variable output often dependent upon the measured temperature of the coolant flowing to the heat exchanger and the exterior air temperature. Such a unit may use air or coolant to transfer heat from the unit to the interior of the vehicle.

All the starting, regulating and run-on functions are controlled fully automatically. The main unit is divided into four main sections – heat exchanger, combustion chamber, fan assembly and control module. Figure 1.37 shows the unit with the coolant inlet (B) and outlet (A) on top of the unit. This feeds the heat exchanger section which allows coolant to flow around the outside of the core. The inside of the core is the combustion chamber which contains a glow plug (3), flame sensor (2) and fuel and air inlet. The combustion is initiated by a glow plug fed with fuel which is quantified by the metering unit (7). The glow plug is switched off after a certain time when the flame has stabilised. The fan assembly/combustion blower (1) provides a fresh supply of air to the combustion chamber. After combustion the heat flows from the inside of the heat exchanger which is then conducted through the exchanger's walls by the coolant. Because the heating power output depends on coolant temperature, sensors are fitted to the heat exchanger housing monitoring coolant temperature to and from the unit. This information is used to govern the unit's heat output to the vehicle's heat exchanger. The output temperature sensor and combustion sensor are used for failsafe purposes in case the unit fails, e.g. overheats. All information is monitored by the ECU (6) which has the ability to communicate with diagnostic equipment. Because the system is electronically controlled, integration into an existing HVAC (Heating, Ventilation and Air-Conditioning) system can be easily achieved.

The booster heater is switched off due to a malfunction if:

1. no ignition takes place after a second attempt at starting (after 90 seconds);
2. the flame is extinguished during operation and a fresh attempt at starting fails;
3. the overheating sensor responds in the event of overheating (125°C);
4. the voltage is over- or undershot;
5. the glow plug, metering pump or temperature sensors or fresh air blower are faulty.

The booster heater can be tested as soon as the ignition is switched on. A fault code can be read out during the diagnostic check.

Use of an A/C system as a heat pump

With the use of highly efficient diesel engines, hybrid vehicles, and electric fuel cell technology, water-based cooling systems often do not offer the heating capacity for passenger compartments. The vapour compression cycle A/C system can be used as a heat pump. This process is explained in section 1.5.

1.3 The basic theory of cooling

An air-conditioner is a generic term for a unit which maintains air within a given space at a comfortable temperature and humidity. To achieve this, an air-conditioning unit must have a heater, cooler, moisture controller and a ventilator.

The principle of an HVAC system:

- heater – adding heat by transferring it;
- cooler – removing heat by transferring it;
- humidity – removing or adding moisture;
- purification – by filtration;
- ventilation – air movement through the vehicle.

The HVAC system creates a comfort zone for the occupants which can be adjusted within a range. Not all humans desire exactly the same environment, variations occur due to different continents, countries, cultures, gender, age or simply due to the type/amount of clothing being worn when inside the vehicle. The system must provide a way of controlling the climate inside the vehicle which is generally referred to as 'climate control'.

Heat

Heat is a basic form of kinetic energy which cannot be destroyed; only it can be converted to or from other forms of energy. In accordance with scientific laws all heat will travel from a hot to a cold surface until the temperatures have equalised. The rate at which heat will travel is dependent upon the difference is temperature between a hot (more energetic molecular movement) and cold (less energetic molecular movement) area. The SI unit for heat energy is the joule. Other measurements include calories and BTU (British Thermal Units). The effects of heat energy are measured using temperature.

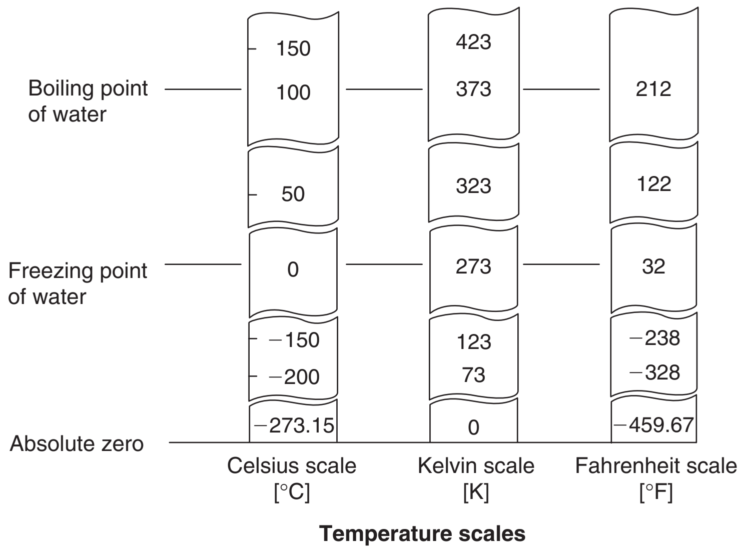


Figure 1.38 Temperature comparison (with the agreement of Toyota (GB) PLC)

Heat intensity

The SI unit for heat intensity is the kelvin, the derived unit is Celsius or Fahrenheit. The kelvin scale is a theoretical scale based on the laws of thermodynamics using absolute zero as the start of its scale instead of zero as used with °C. Scientists state that a temperature called 'absolute zero' is the point at which all heat is removed from an object or substance (a complete absence of molecular movement). The intensity of heat can be measured using a thermometer. This only gives the heat intensity of a substance and not the heat quantity.

The scales on the chart in Figure 1.38 show the boiling point and freezing point of water. It must be noted that this is only true when it occurs at sea level – 101.3 kPa (1.013 bar). Heat intensity within a vehicle for comfort should be between 21 and 27°C (65 and 80°F).

Sensible heat

Heat which causes a change in temperature is called *sensible heat.* As previously stated it can be 'sensed' using a thermometer or pyrometer. Theory tells us that by adding heat to a liquid such as water their will be a proportional increase in its temperature which can be measured on a thermometer scale, e.g.:

> *The amount of heat required to raise the temperature of 1 kg of water by 1°C is 4.2 kJ.*

For example:

> *420 kJ of heat must be applied to 1 kg of water at 0°C to bring it up to the boiling point of 100°C.*

Conversely, the same amount of heat must be removed from the boiling water to cool it down to freezing point.

Alternatively:

1 BTU heat quantity changes the temperature of 1 lb water by 1°F.

Specific heat capacity

Different substances absorb different amounts of heat to cause the same increase in temperature. Specific heat capacity is used to measure the amount of heat required to cause a change in the temperature. The basic unit for specific heat capacity is the *joule per kilogram kelvin (J/kg K)*. Different materials have different specific heat capacity values.

Latent heat and a change of state

Latent heat (hidden heat) is the heat energy required to change the state of a substance without changing its temperature. Heat can have a direct effect on substances when they change state. Evaporation is the term used when enough heat is absorbed by a substance to cause it to change into a vapour. Condensation is when enough heat is removed from a vapour causing it to change to a liquid. When a change of state occurs a great deal of energy is either absorbed or released. This is called the latent heat of vaporisation and the latent heat of condensation.

Example:

2260 kg of latent heat is absorbed when 2 kg of water at 100°C changes state from a liquid to a vapour.

970 BTU of latent heat is absorbed when 1 Ib of water at 212°F changes state from a liquid to a vapour.

This will occur without any change in the thermometer reading.

If ice is heated it will reach 0°C (32°F) then start to melt. This means you will have liquid and a solid existing together. The more heat you add the more the ice will melt with no increase in temperature until no ice exists, then the water will start to increase in temperature (sensible heat). When water reaches 100°C (212°F), any more heat energy added will result in some or all the liquid changing into a vapour. The amount of vapour produced depends on the heat energy available and the pressure above it.

When a substance changes state it can absorb hundreds of times more energy than when it is just increasing in heat intensity. This latent heat is the common process used to transfer heat from the interior of the vehicle to the exterior. The key to successful cooling is to get the liquid or vapour to the point where it wants to condense or evaporate at the right place. To do this we manipulate the system pressure.

The function of the heating system is to increase or reduce heat input to the inside of the vehicle. A typical automotive combustion engine is only about 30% efficient, which means only 30% of the fuel delivered to the combustion engine is converted into usable energy. Some of this energy is transferred to the cooling system which is where the heating system will obtain its heat source for the inside of the vehicle. The rest is lost through exhaust gases and radiation.

Heat can be transferred using one or a combination of three processes – conduction, convection or radiation.

Conduction, convection and radiation

Direct heat movement from one molecule to the next through a substance here the direct heating of a bar one end will travel through the molecular structure to the other end. Some materials

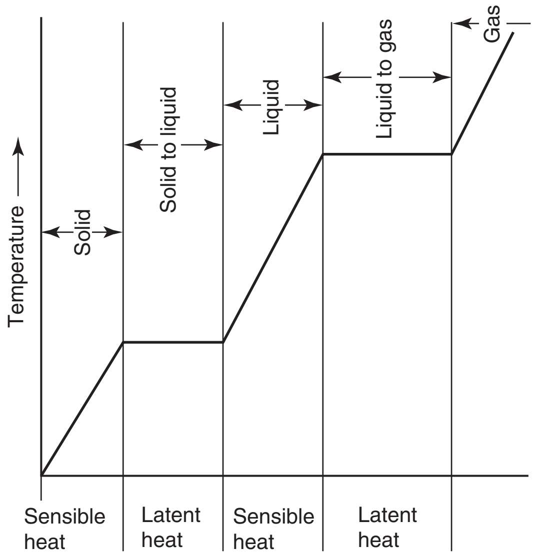


Figure 1.39 Sensible heat and latent heat
(with the agreement of Toyota (GB) PLC)

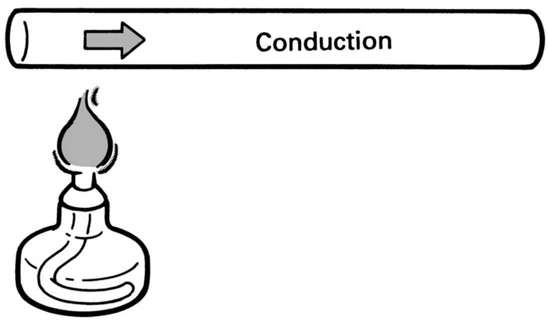


Figure 1.40 Conduction
(with the agreement of Toyota (GB) PLC)

are excellent conductors of heat – aluminium, copper – and other materials act more like insulators – polymers (plastics).

Convection is heat movement *through a medium* like a liquid in a saucepan. Convection is a continuous movement of medium and heat. The medium, liquid or gas, moves and releases heat to the surrounding areas. When heating occurs in a liquid or gas expansion occurs and parts of the substance become lighter than other parts which contain less heat. Natural convection currents occur in any substance which is not heated evenly.

Heat can *travel through heat rays* and pass from one location to another without warming the air they travel through. An example is ultraviolet radiation which travels from the sun. Radiant heat can travel from a warmer object like the sun to a cooler object like the earth's surface. The surface colour and texture affect the heat emitted and absorbed. Colour is not as important as texture; dark *rough* surfaces make better heat collectors than light *smooth* surfaces.

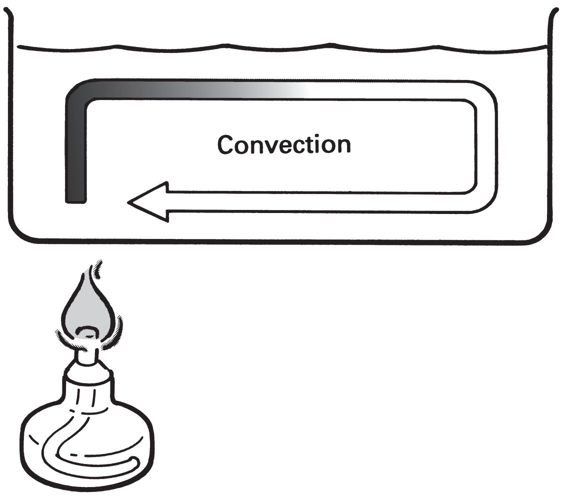


Figure 1.41 Convection
(with the agreement of Toyota (GB) PLC)

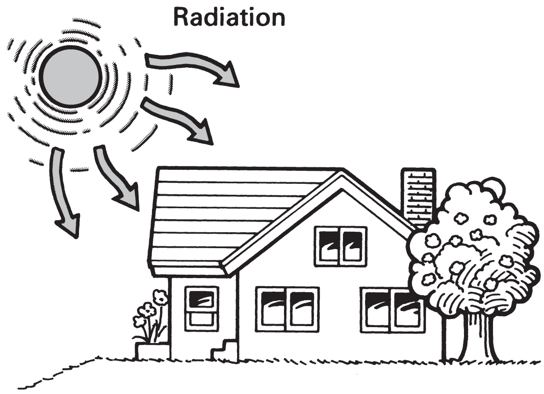


Figure 1.42 Radiation
(with the agreement of Toyota (GB) PLC)

From the engine to the interior

Convection

Convection occurs when material, such as an engine, passes heat to the cooling system of the vehicle. As the potential energy of the fuel is converted to mechanical and heat energy by the engine combustion process, the heat of the engine must be removed. The liquid in the cooling system is pumped through the engine, and the convection process transfers engine heat to the liquid. The cooling system liquid then takes this heated coolant to the radiator. The metal heat exchanger uses the conduction process to remove the heat from the liquid coolant and to the exchanger fins. The radiator fins then pass the heat of the radiator to the passing air flow through the heat exchanger.

Enthalpy

Enthalpy is the measure of the usable energy content of a substance. When a liquid increases in temperature it also increases in enthalpy. When the liquid changes into a vapour through

Table 1.1 Relationship between vacuum and temperature at which water boils

Boiling point of water °C	*Boiling point of water °F*	*kPa*	*bar*
48.9	120.02	−89.60	−0.896
43.3	109.94	−92.50	−0.925
37.8	100.04	−94.80	−0.948
32.2	89.96	−96.50	−0.965
26.7	80.06	−97.80	−0.978
21.1	69.98	−98.80	−0.988
15.6	60.08	−99.60	−0.996
10	50	−100.40	−1.004
4.4	39.92	−100.60	−1.006
−1.1	30.02	−100.80	−1.008
−6.7	19.94	−101.00	−1.01
−12.2	10.04	−101.10	−1.011
−15	5	−101.20	−1.012

latent heat of evaporation it does not increase in temperature but does increase in enthalpy because the energy within the substance increases.

Pressure

Pressure is defined as the force exerted on a unit area by a solid, liquid or gas. The SI unit used to indicate pressure is the pascal (Pa). Other units of pressure are pounds per square inch (psi), kilograms of force per centimetre squared (kgf/cm^2), atmospheres (atm) and millimetres of mercury (mmHg). Atmospheric pressure at sea level is 101.325 kPa (14.6 psi). This is generally shown on a gauge as zero (gauge pressure) unless it is a gauge which measures atmospheric pressure. This means that absolute pressure is atmospheric pressure plus gauge pressure.

Previously it was discussed that water changes state at 100°C. This is if the liquid is at sea level under atmospheric pressure. If you reduce the pressure on the liquid by moving it above sea level or apply a vacuum to it then the boiling point is lowered. If you increase the pressure applied to the liquid by moving it below sea level or specifically applying a pressure on it, then the boiling point is raised.

Table 1.1 shows that if a deep vacuum (1 bar vacuum) is created in a closed system like an A/C system water will boil at 10°C (50°F). This enables technicians to remove moisture from the A/C system using a vacuum pump (refer to Chapter 4). The chart also presents the importance of creating a deep enough vacuum under cold ambient conditions.

If we place a liquid that will readily evaporate at atmospheric pressure inside the box but close the tap, the pressure will build up and increase the boiling point of the liquid (e.g. at a pressure of 5 bar water only boils at 152°C). When the tap is open the pressure will suddenly decrease and the liquid will readily evaporate lowering the temperature by absorbing the heat inside the box.

Critical temperature and pressure

There is a critical temperature which is the maximum point at which a gas can be condensed and a liquid can be vaporised by raising the pressure. Refrigerants R134a and R12 have critical

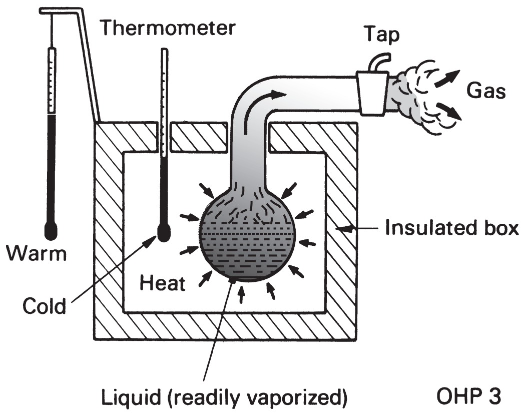


Figure 1.43 Liquid removing heat by changing state (with the agreement of Toyota (GB) PLC)

pressures and temperatures that dictate the maximum pressure/temperature they can be subjected to. If an air-conditioning system operates below the critical points of its refrigerant then they are termed subcritical systems. If they exceed there critical pressure/temperatures then they are termed transcritical systems.

Refrigerants

Refrigerants are the working fluid of the A/C system. An ideal refrigerant would have the following properties:

1. Zero ozone depleting potential and zero global warming potential.
2. Low boiling point.
3. High critical pressure and temperature point.
4. Miscible with oil and remain chemically stable.
5. Non-toxic, non-flammable.
6. Non-corrosive to metal, rubber, plastics.
7. Cheap to produce, use and dispose.

Refrigerant CFC12 – dichlorodifluoromethane

R12 is a CFC (Chloro Fluoro Carbon). The refrigerant consists of chlorine, fluorine and carbon, and has the chemical symbol CCL_2F_2. It was used for many years from the early development of A/C systems up to the mid-1990s when it was progressively phased out leading to a total ban on 1 January 2001 due to its properties which deplete the ozone and contribute to global warming (see Chapter 6, section 6.1). A benefit of R12, when it was originally designed, was its ability to withstand high pressures and temperatures (critical temperature and pressure point) without deteriorating compared to other refrigerants that were around at that time. R12 mixes well with mineral oil which circulates around an A/C system. It is non-toxic in small quantities although does displace oxygen and is odourless in concentrations of less than 20%. R12 can also be clean/recycled. You must not burn/heat R12 to a high temperature (>300°C) with a naked flame because a chemical reaction takes place and phosgene gas is produced. A lethal concentration of phosgene is 0.004% per volume.

R12 properties:

1. It is miscible with mineral oils.
2. It does not attack metals or rubber.
3. It is not explosive.
4. It is odourless (in concentrations of less than 20%).
5. It is not toxic (except in contact with naked flames or hot surfaces).
6. It readily absorbs moisture.
7. It is an environmentally harmful CFC gas (containing chlorine which destroys the atmospheric ozone layer).
8. It is heavier than air when gaseous, hence the danger of suffocation.

Refrigerant HFC134a – tetrafluoroethane

R134a is a known substitute for R12. R134a is an HFC (Hydro Fluoro Carbon). The refrigerant consists of hydrogen, fluorine and carbon, and its chemical symbol is CH_2FCF_3. Because the refrigerant has no chlorine it does not deplete the ozone. R134a is non-toxic, non-corrosive and does contribute to global warming; it is not miscible with mineral oil so synthetic oil, called PAG (Poly Alkaline Glycol), was developed. PAG oil is hygroscopic and absorbs moisture rapidly which means when in use you must ensure that the container is resealed as quickly as possible. R134a cannot be mix with R12 and is not quite as efficient at high pressures and temperatures. R134a can be cleaned and recycled.

R12 and R134a have different size molecules, the R12 molecule is larger. This means the quantity of refrigerant required for an R134a system is higher than an R12. This also requires the flexible hoses and seals including oil to be replaced with compatible R134a components if a conversion from R12 to R134a is required (see Chapter 5). R134a contributes to global warming and will eventually be replaced, certainly within Europe, with another cooling medium which is reported to be less harmful to the environment. R134a is not a drop-in replacement for R12 A/C systems. A number of changes are required to the system components to allow an R12 system to use R134a as a cooling medium (see Chapter 5).

Properties of R134a:

1. It is only miscible with synthetic polyalkylglycol (PAG) lubricants, not with
2. mineral oils.
3. It does not attack metals.
4. It attacks certain plastics, so only use special seals suitable for R134a.
5. It is explosive.
6. It is odourless.
7. It is not toxic in low concentrations.
8. It readily absorbs moisture.
9. It is inflammable.
10. It is heavier than air when gaseous, hence the danger of suffocation near the ground.

Refrigerant blends

The use of alternative refrigerants to R134a and R12 are not accepted by OEM standards. Manufacturers only use the approved R134a refrigerant in vehicle A/C systems. The US has a range of Snap Approved Refrigerants which can be use as 'alternatives' to R12. If blends are used then separate approved service units and acessories must be used to avoid contamination. Strict procedures must be adhered to with regard to record keeping, barrier hose fitment, high pressure release device replacement, service connectors fitment, strict labelling requirements,

Table 1.2 Substitutes acceptable subject to use conditions for CFC-12 in MVACs

Substitute	*Trade name*	*Retrofit/new*
HCFC22		R, N (buses only)
HFC134a		R, N
R406A	GHG, GHG-X3, GHG-12, McCool, Autofrost X3	R, N
GHG-X4, R414A (HCFC Blend Xi)	GHG-X4, Autofrost, Chill-it, Autofrost X4	R, N
Hot Shot, R414B (HCFC Blend Omicron)	Hot Shot, Kar Kool	R, N
FRIGC FR-12, (HCFC Blend Beta), R416A	FRIGC FR-12	R, N
Free Zone (HCFC Blend Delta)	Free Zone/RB-276	R, N
Freeze 12	Freeze 12	R, N
GHG-X5	GHG-X5	R, N
GHG-HP (HCFC Blend Lambda)	GHG-HP	R, N
Ikon 12, Ikon A (Blend Zeta)	Ikon 12	R, N
SP34E	SP34E	R, N
Stirling Cycle		N
CO_2		N
RS-24	RS-24	R, N
Evaporative Cooling		N

Key: R = Retrofit uses, N = New uses

oil replacement and possible seal replacement. Blends currently cannot be recycled using an approved service machine. This means refrigerant has to be sent back to the supplier to be recycled. Blends are compounds made of other refrigerants, R22, R134a, etc. They are either *azeotrope* or *zeotrope*. Azeotrope has a single boiling point while zeotrope are a boiling point range. Zeotrope blends' boiling point range starts when the lighter elements start to boil and ends when the heavier elements boil off. If a leak occurs the blends' lighter elements will vaporise and escape leaving the heavier elements. This is called *fractionising*, which changes the characteristics of the blend.

> *Note* – R134a is the only refrigerant that should be used as a replacement for R12. Retrofitting must be carried out in accordance with SAE requirements (see legislation).

Substitutes

Substitutes are reviewed on the basis of ozone depletion potential, global warming potential, toxicity, flammability, and exposure potential. Lists of acceptable and unacceptable substitutes are updated by the EPA (Environmental Protection Agency) several times each year.

Refrigerant service connectors

To prevent accidental mixing of the refrigerants the SAE (Society of Automotive Engineers) developed guidelines for different service valve connectors for R12 and R134a. If refrigerants are mixed severe damage will occur to the system. R12 uses threaded connections and R134a quick release couplings.

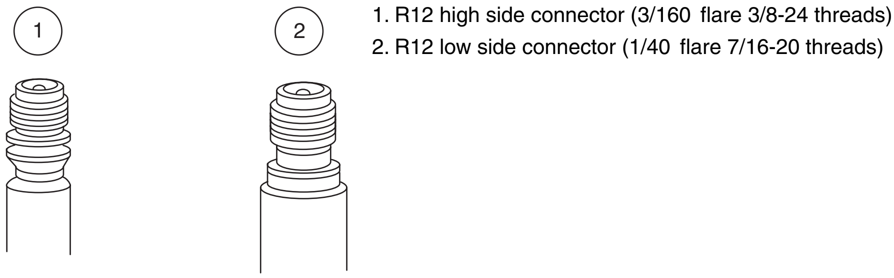


Figure 1.44 R12 threaded service connectors
(reproduced with the kind permission of Ford Motor Company Limited)

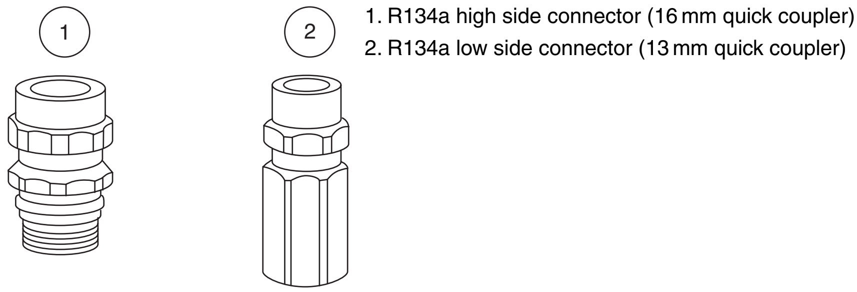


Figure 1.45 R134a quick release type service connectors
(reproduced with the kind permission of Ford Motor Company Limited)

Figure 1.46 R134a blue low pressure connector quick release coupling
(courtesy of Autoclimate)

The service connector forms a valve with the valve core screwed into it. This valve allows the connection of a pressure gauge, A/C machine or control switches/sensors to be removed without draining the system. These are called Schrader type spindle valves. They are similar in design to tyre valves. The needle is held in the closed position by spring force.

Before the coupling is fitted the shut-off valve (blue) must be closed ensuring the valve is not open. Once connected the valve is opened to obtain a reading on the service unit. Blue is allocated to the low pressure side or suction side and red is allocated to the high pressure side or discharge side.

Figure 1.47 shows a threading low pressure R12 connector with ball valve preventing refrigerant loss.

Figure 1.47 R12 low pressure connector 1/4″ SAE Schrader valve 45° end fitting with Goodyear GY5 barrier hose (courtesy of Autoclimate)

Figure 1.48 Schrader valve (courtesy of Autoclimate)

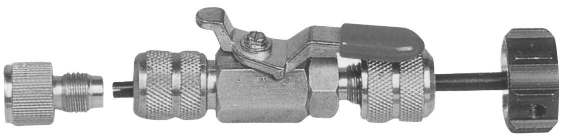


Figure 1.49 Valve core remover and installer with shut-off valves (courtesy of Autoclimate)

The protective cap prevents the valve getting dirty and also provides an additional seal when the system is working. The protective caps must be screwed on again after the system is filled. The service connector valves must seal completely. To check, apply a few drops of compressor oil to the needle. If bubbles are formed, the valve is leaking and the valve core must be renewed.

Tools are available to remove Schrader valves without draining the system, providing there is sufficient space.

Hose material

A/C systems are designed to use as little flexible hoses as possible due to leakage. Aluminium extruded tubing is generally used with the exception of the compressor which uses flexible hoses because it is connected to the engine. Modern hoses for R134a use an inner lining of nylon due to the size of the R134a molecule and to reduce moisture ingression. Covering the nylon is an external tubing of Neoprene. Polyester braid is used as reinforcement with a final

Table 1.3 Comparative data

	Unit	*R12*	*R134a*
Chemical name		Dichlorodifluoromethane	Tetrafluoroethane
Colour of storage bottle		White	Light blue
Thread on container		7/16″	8/16″
Connector size/type		1/4″ flare 7/16-20 threads	Low quick couple 13 mm
		3/16″ flare 3/8-24 threads	High quick couple 16 mm
Lubricant		Mineral oil	PAG
Desiccant		XH-5	XH-7 or XH-9
Boiling point at 1 bar	°C	−29.8	−26.5
Critical temperature	°C	+112	+101.15
Critical pressure	bar	41.48	40.68
Molar mass	g/mol	120.92	102.03
Liquid density +20°C	kg/l	1.33	1.23
Ozone reduction factor		0.96	0.0
Hot house factor		3.1	0.3
Coldness gain	kj/m^3	1495	1455
Cooling efficiency		4.3	4.2

covering of PVC (Polyvinyl Chloride). R12 hose is constructed in the same way but without the nylon lining due to the larger size molecule. Electric compressors may remove the need for any flexible hoses. The government and environmental groups are placing increased pressure on zero leak rates.

OEM (Original Equipment Manufacturers) will always advise you to use the correct refrigerant for the correct system. Deviation from the original set-up should only occur if you are converting an R12 system to an R134a.

The pressure/temperature relationship of R134a

The graph in Figure 1.50 shows the pressure/temperature curve for refrigerant R134a.

The graph shows the refrigerant to be in a gaseous/vapour state above the curve and a liquid below the curve.

1. The refrigerant is in a gaseous/vapour state and if the temperature is kept constant and the pressure is increased then the refrigerant will condense into a liquid.
2. If the pressure is kept constant and the temperature is reduced then the refrigerant can be condensed into a liquid.
3. If the temperature is kept constant and the pressure is reduced then the refrigerant will evaporate into liquid/vapour.
4. If the pressure is kept constant and the temperature is increased then the refrigerant will evaporate into liquid/vapour.

Comfort – humidity

Humidity is the term used to describe the wetness or dryness of air. The air around us contains a percentage of water vapour. Humans perspire (sweat) which evaporates and cools the surface of the skin by convection. If humans are in hot humid conditions then this makes us feel sweaty,

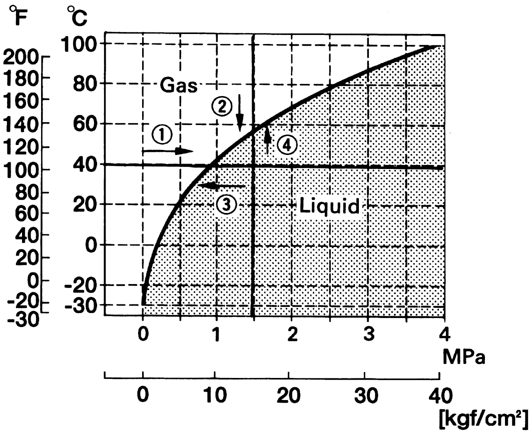


Figure 1.50 Pressure/temperature curve R134a (with the agreement of Toyota (GB) PLC)

uncomfortable, anxious and can induce stress. A fan to force air over the occupant of a vehicle can improve the evaporation rate and improve comfort.

There are generally two ways to measure humidity, relative humidity and absolute humidity. Relative humidity is the most common measurement and tells us how much water vapour by weight the air actually contains compared to how much it could contain at that given temperature. As an example, if the relative humidity is 50%, the air could hold twice as much vapour as it does at that given temperature. The amount of vapour that the air can hold changes with its temperature. If the air warms up then it can hold more vapour which would reduce the relative humidity because it could hold more vapour than what it was actually carrying. If the air cools then its relative humidity reduces because it can now hold less.

Absolute humidity is the amount (by weight) of vapour that the air contains compared with the amount of dry air. When air becomes saturated with water and then cools the relative humidity will eventually (depending on the rate of cooling) become 100%. The temperature is called the 'dew point' of air for the absolute humidity. If the air cools any further then the vapour it contains will condense.

The significance of this information is the control of the humidity within the A/C system. Humidity is controlled by the surface area of the evaporator and the volume and flow of air travelling through it. The cold surface of the evaporator causes the moisture in the air to condense and cover the surface in water droplets. This reduces the moisture content thus drying the air and improving comfort. Relative humidity for comfort levels is generally about 60%.

Dry bulb temperature

This is the temperature indicated by an ordinary thermometer used to measure air temperature.

Wet bulb temperature

In a wet bulb thermometer the heat sensitive bulb of a glass tube thermometer is wrapped in a gauze, one end is suspended in a water container to allow the water to be drawn upwards by capillary action and moisten the bulb. The moisture robs a percentage of the heat surrounding the bulb which is dependent upon how easily the water can evaporate. The temperature that is registered is referred to as the 'wet bulb temperature'. Some equipment suppliers sell as an accessory a probe with a wet sock which attaches to a multi-meter allowing the electronic measurement of temperature. The sock can be removed to obtain the dry bulb temperature. As

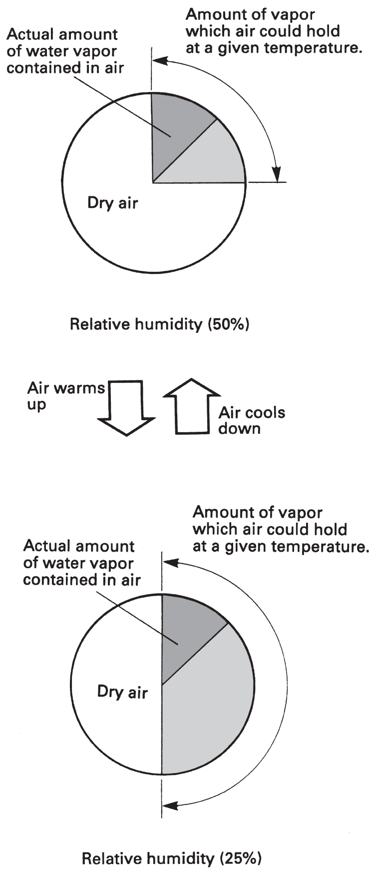


Figure 1.51 Humidity graph
(with the agreement of Toyota (GB) PLC)

discussed, relative humidity is measured by comparing the wet bulb temperature against the dry bulb temperature. Instruments that contain both measuring devices are called psychrometers.

As an example – in Figure 1.52 the graph shows the wet bulb temperature 19.5°C (follow diagonal line), dry bulb temperature 25°C (horizontal line) and relative humidity = 60% (point where both intersect).

After measuring the dry and wet bulb temperatures of the air entering the evaporator and the air exiting the centre vent inside the vehicle the graph can be used to calculate the relative humidity and compare the two results ensuring good evaporator performance. Example, relative humidity of the ambient air entering the HVAC unit – 70%, relative humidity of the air exiting the centre vents inside the vehicle – 50%.

Humidity sensor

See Chapter 3, section 3.2.

1.4 Vapour compression refrigeration

Currently the most common cycle used in automotive applications is the vapour compression cycle, e.g. R12 and R134a closed systems. To understand the vapour compression cycle and

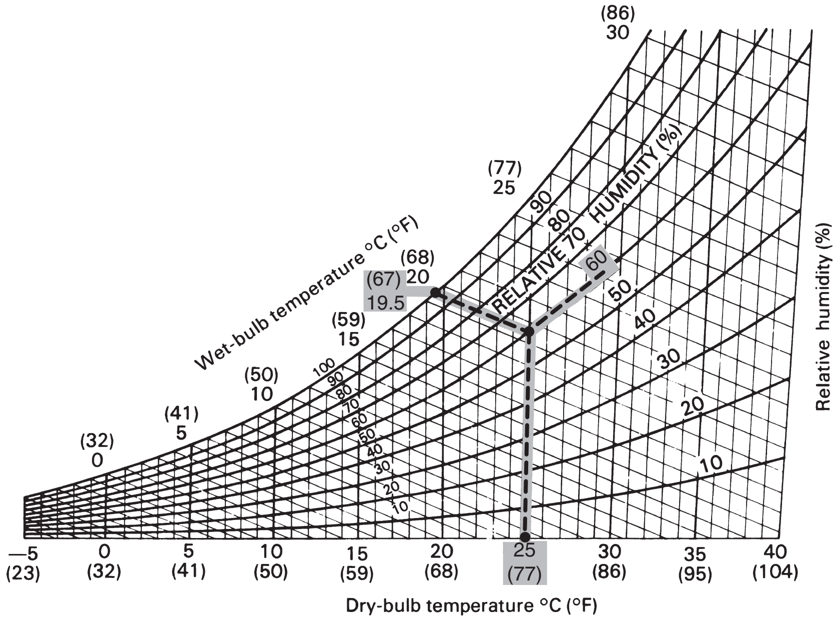


Figure 1.52 Psychometric chart
(with the agreement of Toyota (GB) PLC)

other cycles it is important to understand the types of changes that a refrigerant goes through when used in an A/C system. This is explained using a pressure/enthalpy diagram (Figure 1.53).

A refrigerant in the 'subcooled' liquid region point a is at a temperature which is below its boiling point. If heat is continually added while maintaining constant pressure, the refrigerant's temperature and enthalpy will increase. Its state will eventually approach 'saturated liquid' point b. This is where the liquid will start to vaporise. As the heat is continually added the liquid vaporises and continues to increase in enthalpy but not increase in temperature. The 'saturated liquid' vaporises until it becomes a 'saturated vapour' point b–c. The 'saturated vapour' at point c has no liquid because is has completely vaporised. The heat that is absorbed through the transition from 'saturated liquid' to 'saturated vapour' is called the latent heat of evaporation (heat is absorbed without any increase in temperature). With additional heat still available to the 'saturated vapour' the temperature increases causing the refrigerant to become 'superheated vapour' point d.

At this point the heat addition causes an increase in temperature. The saturated liquid and saturated vapour curves meet at a point called the 'critical point'. This point has a corresponding critical pressure and critical temperature. Above the critical pressure the refrigerant is in a state called the 'supercritical region'. The supercritical region is where heat addition or removal does not cause a distinctive liquid vapour phase transition.

The ideal vapour compression cycle

The following applies the vapour compression cycle as an ideal cycle within an automotive A/C system. The Figure 1.54 pressure/enthalpy diagram shows the beginning of the cycle as the refrigerant enters the compressor as a 'saturated vapour' at point 1. The refrigerant is compressed adiabatically (the compressor is 100% efficient and no heat is removed by the process) and becomes a 'superheated vapour' due to the increase in pressure, temperature and enthalpy

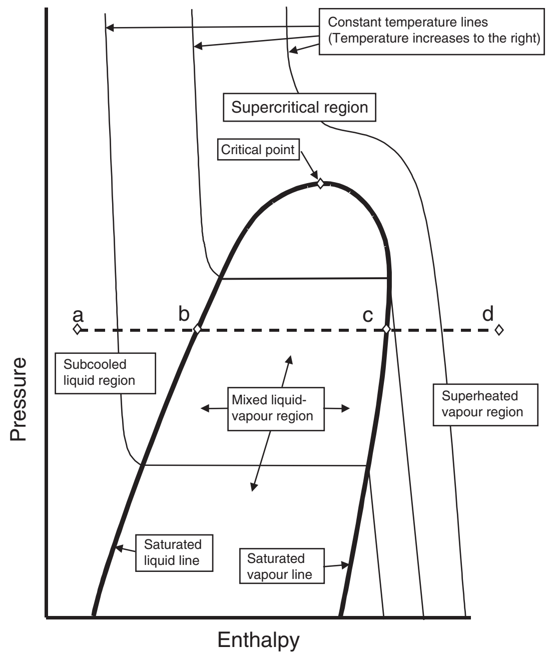


Figure 1.53 Pressure/enthalpy diagram
(Still Awaiting Permission)

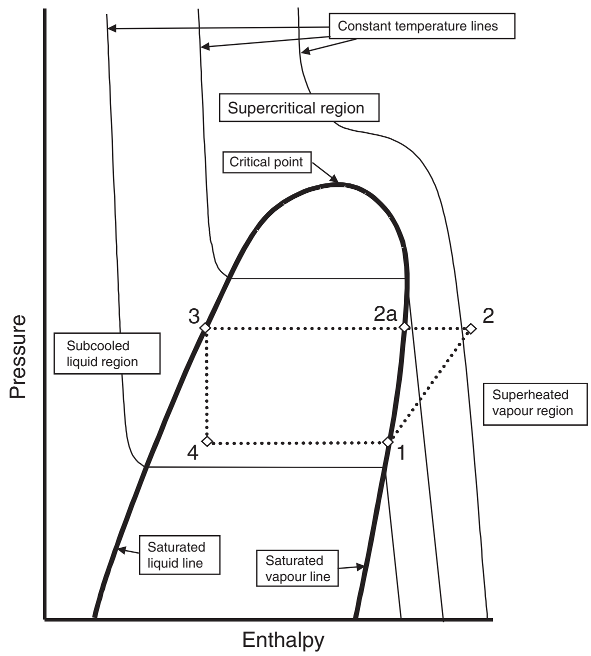


Figure 1.54 Ideal vapour compression cycle
(Still Awaiting Permission)

as shown by point 2. The refrigerant by this point is above the temperature of the outside air. The refrigerant leaves the compressor and enters the condenser (heat exchanger). The condenser allows the heat to transfer to the outside air effectively removing enough heat to change into a saturated vapour from a superheated vapour point 2a. This has lowered the temperature of the refrigerant. Now the refrigerant is a 'saturated vapour' the pressure and temperature are kept constant but heat is still being removed and only the enthalpy continues to decrease. The vapour begins to condense to liquid (latent heat of condensation). Condensation continues until all the vapour is a 'saturated liquid' point 3. The refrigerant leaves the condenser as a saturated liquid and travels to an expansion valve or fixed orifice tube. The refrigerant now undergoes an 'isenthalpic' expansion process (constant enthalpy). The process significantly reduces the temperature and pressure of the refrigerant while the enthalpy remains the same. A small amount of liquid refrigerant (flash gas) vaporises during expansion but most of the refrigerant is liquid at a temperature lower than that of the outside air (air inside the vehicle or entering the vehicle) point 4. The refrigerant flows through the evaporator which acts as a heat exchanger that transfers heat from the air flowing through its fins to the refrigerant flowing through its coils. The refrigerant absorbs the heat increasing in enthalpy while the temperature and pressure remain the same. The liquid refrigerant vaporises until it becomes a 'saturated vapour'. The saturated vapour then travels to the compressor to start the cycle again.

The real world operation

The real world operation of the A/C system deviates from the ideal cycle. It is difficult for condensation and evaporation to end exactly on the liquid/vapour saturation lines. This is particularly difficult due to the fact that the system has to operate under so many varying conditions. To ensure an acceptable performance under all loads the condensers are designed to 'subcool' the refrigerant to a certain amount to ensure that only liquid refrigerant flows to the expansion device for optimum performance (also one of the jobs of the receiver drier). If vapour flows to the expansion device it reduces the flow of refrigerant significantly. Evaporators are generally designed to slightly 'superheat' (TXV systems) the refrigerant to ensure that only vapour flows to the compressor and no liquid (except for oil circulation 3%). There are also pressure drops across components like the condenser and evaporator which cause deviation from the ideal constant pressure process. Fixed Orifice Valve (FOV) systems use a fixed orifice diameter which is designed for optimum flow at high compressor and vehicle speeds. Poor performance at idle conditions can occur where there is a possibility of the evaporator being excessively flooded. Some flooding is advantageous with the FOV system. This is to increase cooling capacity and reduce 'hot spots', which are areas of reduced heat transfer caused by poor refrigerant distribution. Too much flooding reduces compressor performance.

1.5 Alternatives cycles

Pressure from the European Union for more environmentally friendly A/C systems has forced manufacturers to look for alternative refrigerants or technologies for HVAC units. A great deal of controversy exists on which technology the EU, US and the automotive industry wants to supersede R134a or in fact just improve the current R134a into a leak-free system. The EU will phase out R134a from 2011 with a complete ban on its use by 2014 to 2017 (dates to be finalised). Possible alternatives are within this section although it seems inevitable that CO_2-based A/C systems will replace the R134a system which is currently used.

A list of possible alternative are:

- CO_2-based system (R744);
- absorption refrigeration;
- secondary loop system (HFC152);
- gas refrigeration (R729);
- evaporative cooling;
- thermo electric cooling (Peltier effect).

The production of R744 (CO_2)-based HVAC systems will be included on vehicles being mass produced by 2008. The following information has been provided to aid the reader in predicting what refrigerant and accompanying technology will be implemented to supersede R134a.

The CO_2 (R744)-based refrigeration cycle (transcritical system)

Refrigeration and air-conditioning systems where the cycle incurs temperatures and pressures both above and below the refrigerant's critical point are often called transcritical systems. Transcritical systems are somewhat similar to the subcritical systems described above although they do have some different components.

Figure 1.55 illustrates the transcritical vapour compression process. It begins when the superheated refrigerant enters the compressor at point 1. Its pressure, temperature and enthalpy are increased until it leaves the compressor at point 2 located in the supercritical region. Next the refrigerant enters the gas cooler whose function is to transfer heat from the fluid to the environment. Unlike the condensing process in the subcritical system, the refrigerant has not undergone a distinct phase change when it leaves the gas cooler at point 3. Note that this gas cooling

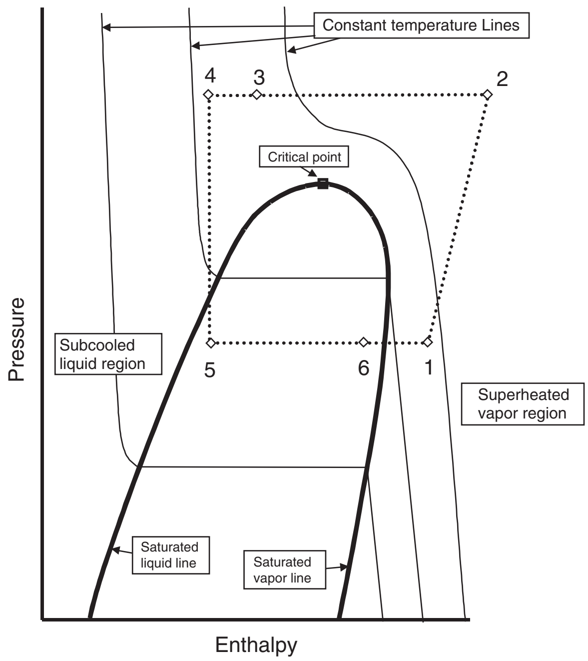


Figure 1.55 Pressure/enthalpy graph transcritical system using R744 (CO_2) (Still Awaiting Permission)

process does not occur at constant temperature. The cooled gas then enters an internal heat exchanger (sometimes called a 'suction line heat exchanger'), which transfers heat to that portion of the refrigerant that is just about to enter the compressor.

This results in additional cooling of the refrigerant to point 4 on the figure, improving performance at high ambient temperatures. From there, the flow undergoes a constant-enthalpy expansion process that decreases its temperature and pressure until it exits at point 5 in the mixed liquid/vapour region, at temperature and pressure well below the critical values. Next, the refrigerant enters an evaporator where it absorbs heat from the cooled space and its enthalpy and vapour fraction gradually increase until it exits at point 6. Finally, the flow enters the internal heat exchanger where it absorbs more heat, until it is ready to enter the compressor again at point 1 to repeat the cycle.

> *Note* – the R744 cycle will also work in the subcritical region (i.e. some condensation in the gas cooler will take place) in case the ambient temperature is considerably lower than the critical temperature of R744, which is about 31°C.

System operation

Figure 1.56 shows a R744 closed loop A/C system capable of acting as a heat pump. The increased use of highly efficient diesel engines, particularly direct injection models as presently occurring

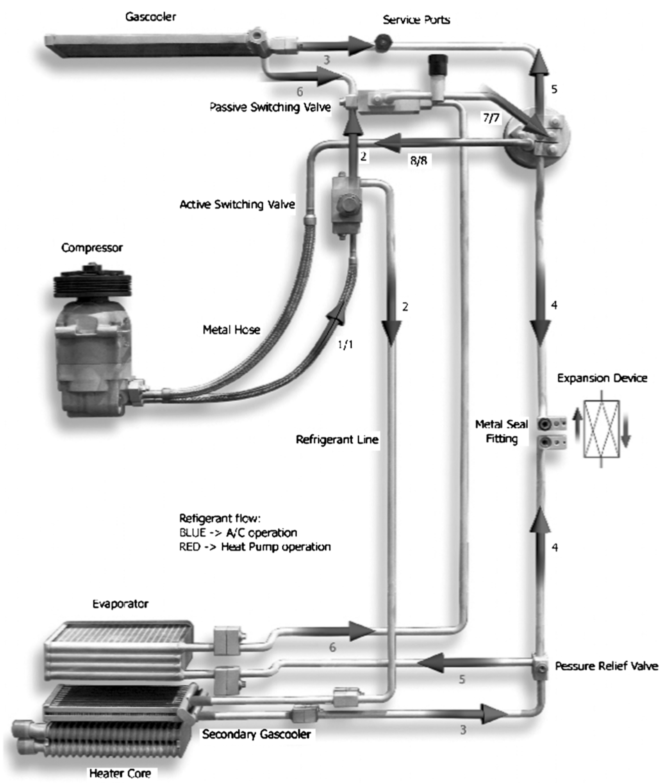


Figure 1.56 System layout for A/C and heat pump operation (© 2005 Visteon All Rights Reserved).

in Europe, and the anticipated increase in the use of hybrid vehicles, means that engine coolant will no longer have the customary temperatures and capacities for acceptable passenger compartment heating and window defrosting/demisting operations. However, a heat pump can be used to heat to the passenger compartment boosted to temperature levels to which vehicle occupants are accustomed.

The diagram (also reproduced in colour in the plate section) shows arrows in blue which represent refrigerant flow when in A/C mode and red arrows when in heat pump mode.

A/C operation (blue arrows)

1. Compressor
   Superheated refrigerant enters the compressor (temperature 30°C, pressure 35 bar). The refrigerant is compressed increasing its pressure, temperature and enthalpy (130 bar, 160°C). The given values represent a high load point.
2. The gas cooler (replaces the condenser)
   The refrigerant enters the gas cooler (via the active switching valve), upon entering the gas cooler the superheated gas allows heat to be transferred to the walls of the gas cooler and air travelling through it. The refrigerant does not go through a distinct phase change although its temperature (at the gas cooler outlet a few kelvin above inlet air temperature, for example 40°C for a 35°C ambient temperature) and enthalpy reduce. The refrigerant is still operating above its critical point.
3. The accumulator/internal heat exchanger
   The refrigerant flows to the high pressure side of the internal heat exchanger which removes heat by transferring it to the refrigerant that is about to enter the compressor. This again reduces the refrigerant's temperature (30°C).
4. Electronic expansion valve
   The refrigerant flows to the electronically controlled expansion device which creates a large pressure drop promoting the constant-enthalpy expansion process. The reduced pressure and temperature of the refrigerant now allows the device to operate below its critical point. The refrigerant is now a mixture of liquid and a flash vapour having the ability to change state with additional heat input.
5. Evaporator
   The refrigerant flows into the evaporator absorbing heat through evaporation until it exits the evaporator as a saturated vapour.

6/7. Accumulator/Internal heat exchanger
   The refrigerant flows (through the passive switching valve) to the accumulator/internal heat exchanger. This component combines the accumulator and internal heat exchanger functionalities into one part. The internal heat exchanger section enables the refrigerant to become slightly superheated. The accumulator portion separates the liquid and gaseous phase, stores the unused liquid refrigerant and allows the compressor oil together with the gaseous refrigerant to return to the compressor for lubrication.

8. Slightly superheated refrigerant flows back to the suction side of the compressor and the process repeats.

Note – temperatures and pressures are approximate and are dependent on system load.

Heating operation (red arrows)

Heating is achieved by directing the flow of heated refrigerant to a secondary gas cooler positioned inside the vehicle which heats the incoming/recycled air and is distributed through conventional ducting. The refrigerant then flows to the accumulator/heat exchanger and external gas cooler which is positioned at the front of the vehicle.

1. Compressor
   For an assumed ambient temperature of −18°C, the refrigerant enters the compressor at a temperature of about −20°C and a pressure of 18 bar. The refrigerant will be compressed to about 90 bar at 90°C.
2. The secondary gas cooler
   The active valve will divert the flow that – in an A/C cycle – would usually go to the gas cooler, to the secondary gas cooler. Upon entering the gas cooler the superheated/high temperature gas allows heat to be transferred to the walls of the gas cooler and the air travelling through it. The refrigerant is still operating above its critical point. Both temperature and enthalpy reduce.

3/4. The electronic expansion device
   The refrigerant flows to the electronically controlled expansion device which creates a large pressure drop promoting the constant-enthalpy expansion process. The reduced pressure and temperature of the refrigerant allows it to operate below its critical point. The refrigerant is now a liquid and flash vapour having the ability to change state with additional heat input. Note that for a heat pump cycle the expansion device needs to be a bi-directional type as flow enters from both sides.

5. The accumulator/internal heat exchanger
   The internal heat exchanger (IHX) section has no duties in the heat pump cycle (both the former high and low pressure sides of the IHX are now located on the low pressure side of the cycle) and is only a passage for the refrigerant.
6. The gas cooler
   The refrigerant flows from the accumulator/internal heat exchanger to the gas cooler, which in fact now acts as the evaporator for the heat pump cycle, where it will absorb more heat to change from a saturated vapour to become slightly superheated.
7. The accumulator/heat exchanger
   The passive valve collects the flow of the heat pump branch of the circuit and directs the flow to the accumulator/internal heat exchanger. Again, the IHX is pretty much without function, but the accumulator section acts exactly as in A/C operation.
8. The compressor
   The refrigerant flows from the accumulator/heat exchanger back to the compressor and the process repeats itself.

   Note – pressure and temperature figures depend on system load.

Heat pump operation will only be used at very cold ambient temperatures allowing for faster defrost and/interior warm-up. It does not replace the normal heater core and is just a supplement. Thus the mixed A/C/heater mode is still available, but there will be no combined A/C/heat pump operation (as both functions rely on the same refrigerant circuit). A/C will continue to be used for dehumidification in warmer ambient temperatures or during comfort drive, assisted by the normal heater core for reheating. Removing particles is the duty of the air filter that is located upstream of the evaporator.

R744 properties

R744 has a corrosive effect on polymers so metal pipes are used. R744 is non-flammable and relatively cheap compared to R134a. CO_2 is also easier to recycle than R134a.

Table 1.4 Properties of R744

	R744
Operational mode	Transcritical
High pressure	60–140
Low pressure	35–50
Max gas temperature	Up to 180°C
A/C line diameters	10–12
A/C line fittings type	Axial metal
Flexible hose material	Steel
Compressor displacement (cm^3)	20–33
Compressor housing diameter (mm)	100–120
Expansion device	Electronic valve or mechanical orifice
Front end heat exchanger	Gas cooler

(Specifications and descriptions contained in this book were in effect at the time of publication. Visteon reserves the right to discontinue any equipment or change specifications without notice and without incurring obligation (07/05).)

Component information

Sanden and LuK have been assisting with research and development of compressor designs for R744 systems.

- Research in 2000 was based on compressor LVT (30–36 cm^3), the parts are interchangeable with compressor VDA (160 cm^3) – R134a.

Maximum pressures and temperatures to withstand:

- high side 16.0 MPa (2320 PSI);
- low side 12.0 MPa (1740 PSI);
- high side 180ºC (356ºF) (discharge temperature).

Possible lubricants for the system

POE or PAG are the most likely options. Surplus oil will be stored in the accumulator and sucked back to the compressor via an oil bleed hole in the accumulator through the suction line. Refrigerant filters will most likely be applied in an R744 system, one location could be within the accumulator, another one in front of the expansion device.

Accumulator/Internal heat exchanger

The accumulator is required to store lubricant for the compressor operation. The internal heat exchanger acts as a heat exchanger to increase cooling capacity which is required mainly at high ambient air temperatures. The accumulator also ensures that no liquid refrigerant enters the compressor during the system operation.

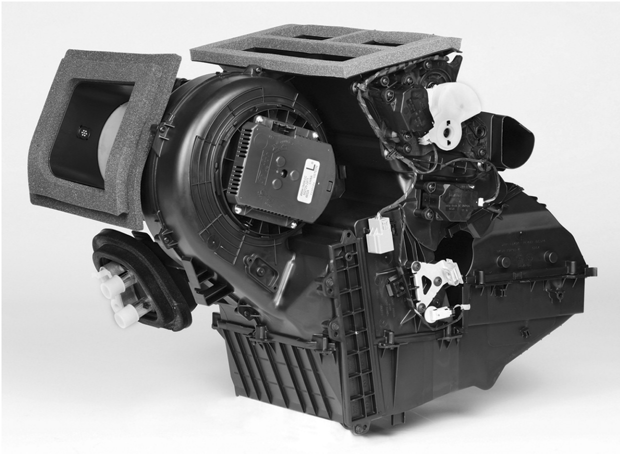


Figure 1.57 Mutli zone HVAC unit for CO_2 application

Gas cooler

The efficiency of the system's operation is highly dependent on the air flow through the gas cooler ensuring enough heat is removed or absorbed.

Expansion valve

A solenoid operated valve which can be operated by a high frequency pulse width modulated signal or an analogue DC voltage.

Visteon multi zone modular HVAC system

The modular multi zone HVAC system offers manufacturers the flexibility to personalise the HVAC system depending on model specification and provides up to four temperate controlled zones from one unit (this number of temperature controlled zones is usually provided by two or more units). Modular units allow for mass production of common components gaining efficiencies of scale while still providing flexibility to the customer.

System benefits:

- All metal sealing promotes no leak concept.
- Cross platform usage – modular multi zone design.
- Heat pump facility.
- Full electronic control.
- Low Global Warming Potential (GWP) (1) and zero Ozone Depleting Potential (ODP).
- Improvement in fuel economy.
- No additional fuel or electric heater required.
- Reduction in emissions.

Negative aspects:

- A higher level of technology is required and additional components are necessary.
- Additional cost to suppliers exists due to large investment in research and development (whether this cost will be passed on to the consumer or absorbed by the OEM is speculation).

- There will be an impact on the service and training industry requiring new knowledge, skills, equipment and possibly a certificate of competence to service and repair such systems.

Absorption refrigeration

The absorption refrigeration cycle is attractive when there is a source of inexpensive or waste heat readily available. This cycle uses a refrigerant that is readily soluble in a transport medium. In brief, the condensation, expansion and evaporation processes are identical to those of the vapour/compression cycle. But instead of the latter's compression process, the absorption cycle's liquid transport medium absorbs the refrigerant vapour upon leaving the evaporator, creating a liquid solution. This solution is then pumped to a higher pressure, and then heat is used to separate the refrigerant from the solution, whereupon the high pressure refrigerant flows to the condenser to continue the familiar cycle. The equipment used to accomplish the solution/dissolution processes is complex and heavy, but the advantage lies in the low work input requirement to raise the pressure of a liquid solution as compared to that required for compressing a gas. If the heat utilised is otherwise wasted heat, the low operating costs of absorption systems can be quite attractive. The two most common refrigerants used in absorption systems are ammonia, with water as the transport medium, and lithium bromide in water. However, toxicity issues with ammonia require safeguards, adding to system cost and complexity. Lithium bromide can be corrosive to most common materials, again adding to cost and complexity. Absorption systems are used mostly in large non-vehicular building applications, though occasionally there has been advocacy of their use as mobile air-conditioning systems.

Secondary loop system HFC152a

HFC152, which is flammable, must be used in a 'secondary loop' A/C system that uses a chiller to transfer cooling from the refrigerant in the engine compartment to coolant that is circulating into the passenger compartment. The secondary loop is required as opposed to a primary loop using a hydrocarbon-based refrigerant because if a leak occurs in the evaporator and hydrocarbons are released then an explosion could occur.

The primary loop (refrigerant circuit) operates in the same manner as the vapour compression cycle using a hydrocarbon-based refrigerant instead of R134a. It is positioned under the bonnet. The secondary system (coolant system) positioned inside the vehicle uses brine as a cooling medium which is under pressure by the circulating front and rear pump to transfer the heat from the front and rear coolers to the cooling medium. The reservoir is required to allow for the expansion of the coolant. The system is a dual A/C system with front and rear coolers. This system allows the easy addition of multiple cooling points with no additional expansion device. The refrigerant charge in the primary system is about half when compared to an R134a system with the same HVAC specification.

System benefits:

- Wide choice of refrigerants can be used.
- Enhances city traffic and idle cooling performance.
- Potential for targeted cooling (e.g. seats).
- Reduces refrigerant charge and leakage.
- Potential for elimination of heater core resulting in smaller HVAC case and cost savings (single heat exchanger for heating and cooling).
- Refrigerant NVH reduction – front and rear.
- Eliminates refrigerant maldistribution (coolant exhibits more uniform temperature distribution than refrigerant).

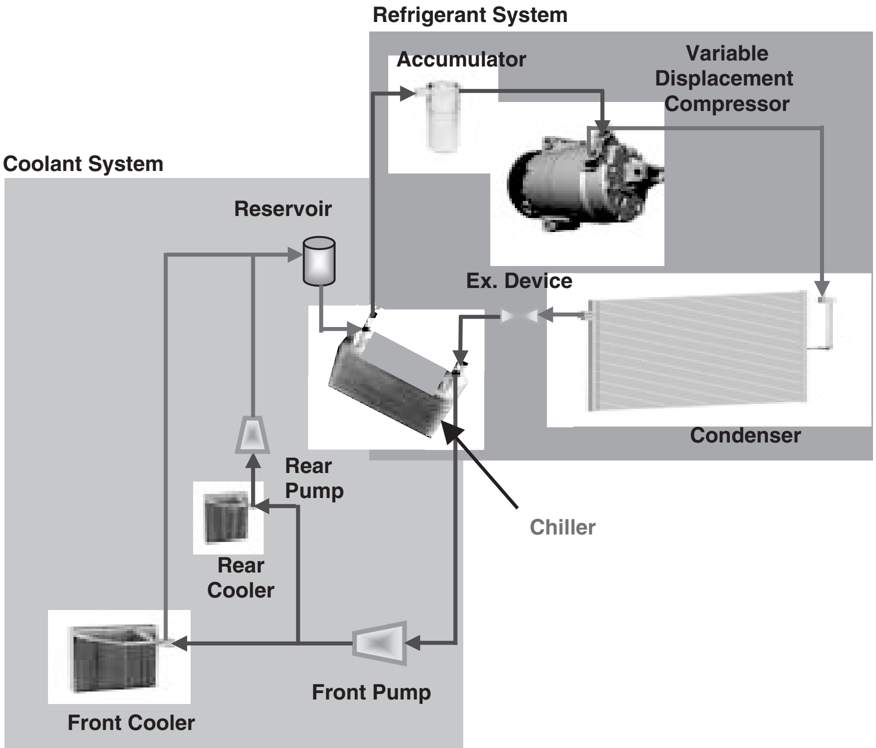


Figure 1.58 HFC152a secondary loop system with front and rear cooler (courtesy of Volvo)

System drawbacks:

- The use of flammable refrigerant.
- Cost of the system.
- Energy penalty.
- Weight of the system.

Gas refrigeration

The gas refrigeration cycle

In the past the gas refrigeration cycle, which is common on aircraft, has been considered for the automobile industry. Research on the use of an air refrigeration system exists and cannot be excluded as a future option due to this fact.

The gas refrigeration cycle is appropriately named due to the refrigerant remaining in a gaseous state throughout the entire cycle. R729, otherwise known as air, is used as the refrigerant medium.

The pressure enthalpy diagram for a closed gas refrigeration system operates outside of the phase transition of the refrigerant so that the saturation curves do not appear on the diagram unlike the vapour compression cycle.

To aid the explanation of the system operation a Jaguar aircraft has been used for illustration (see Figure 1.59).

Figure 1.59 Jaguar aircraft
(courtesy of RAF Coltishall)

Figure 1.60 Gas turbine engine showing the outlet feed to the A/C system
(courtesy of RAF Coltishall)

The refrigerant (air) enters a rotary compressor to raise its pressure and enthalpy. Air charge is taken from both the compressors via an outlet as shown circled in Figure 1.60.

Only compressed gas at a temperature of about 190°C enters the A/C system because the feed is situated on the outlet of the compression stage and not ignition.

The air then travels to a primary heat exchanger where it gives up heat at constant pressure. The exchanger has ram air flowing through it to reduce the temperature of the air feed from the gas turbine engines.

In Figure 1.61 the primary heat exchanger is fitted along the spine of the aircraft (large circle) and is fed from the gas turbine engine (small circle).

The gas then flows to a turbine unit (cold air unit) where it expands reducing in enthalpy, temperature and pressure. Some units connect the turbine to a compressor to recover some of the energy given up during isenthalpic expansion. The air is at a temperature of about 100°C upon leaving the turbine (cool air unit).

Upon leaving the turbine the gas flows to a secondary heat exchanger, situated behind the cockpit. Cabin air circulates through the fins of the heat exchanger releasing heat and then a water extractor removes moisture in the air.

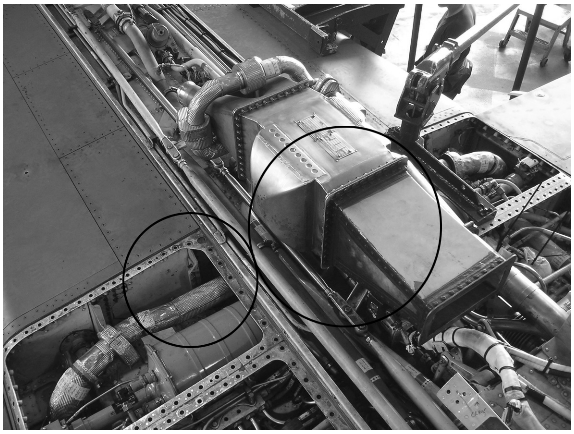


Figure 1.61 Exposed airframe (courtesy of RAF Coltishall)

Figure 1.62 Secondary heat exchanger inlet (courtesy of RAF Coltishall)

The air is then distributed around the cabin and auxiliary equipment situated on the aircraft. Because the cabin is pressurised, air is bled through two discharge valves in the aircraft fuselage. This means that the system is an open A/C system because the air does not flow back to the compressor to flow through the process again unlike a closed system.

The system can be operated manually or automatically to control the internal temperature of the cockpit. Heating is achieved by bypassing the heat exchangers thus transferring heat laden gas to the air distribution system. This is electronically sensed using thermistors and directed using control flaps.

Evaporative cooling

The latent heat of vaporisation of water can provide cooling to vehicle occupants. A crude approach is to spray one's face with a water mist, then place the head outside the window of a moving vehicle into the free air stream – the evaporating water carries away heat from the skin. There have been devices, mostly in the 1950s – 'The Weather Eye' – that worked on evaporative

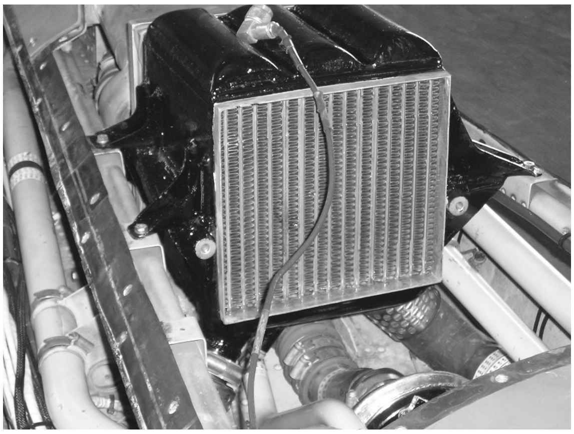


Figure 1.63 Secondary heat exchanger (courtesy of RAF Coltishall)

cooling. They consisted of a box or cylinder fitted to the window of the vehicle. The intake of the unit would allow air to enter from outside and travel through a water soaked wire mesh grille and excelsior cone inside the unit. The water would evaporate due to absorbing the heat in the air and travel through the outlet of the unit which acted as a feed to the inside of the vehicle. At one time, these devices had a certain attractiveness, particularly in hot, low humidity regions like the US southwest. However, their performance compared to modern vehicular air-conditioning systems is generally inadequate and they currently do not have significant popularity.

Thermo electric cooling (Peltier effect)

The basic concept behind thermoelectric (TE) technology is the *Peltier effect* – a phenomenon first discovered in the early 19th century. The Peltier effect occurs whenever electrical current flows through two dissimilar conductors; depending on the direction of current flow, the junction of the two conductors will either absorb or release heat.

Semiconductor material, usually bismuth and telluride, are generally used within the thermoelectric industry. This is due to the type of charge carrier employed within the conductor (see Chapter 3). Using this type of material, a *Peltier device* can be constructed. In its simplest form it consists of a single semiconductor 'pellet' which is soldered to electrically conductive material on each end (usually plated copper). In this 'stripped-down' configuration (Figure 1.65), the second dissimilar material required for the Peltier effect is the copper connection which also acts as a conductor for the power supply.

N type

Once impurities are added to a base material their conductive properties are radically affected. For example, if we have a crystal formed primarily of silicon (which has four valence electrons), but with arsenic impurities (having five valence electrons) added, we end up with 'free electrons' which do not fit into the crystalline structure. These electrons are loosely bound. When a voltage is applied, they can be easily set in motion to allow electrical current to pass. The loosely bound electrons are considered the charge carriers in this 'negatively doped' material, which is referred to as 'N' type material. The electron flow in an N type material is from negative to positive. This is due to the electrons being repelled by the negative pole and attracted by the positive pole of the power supply.

P type

It is also possible to form a more conductive crystal by adding impurities which have one less valence electron. For example, if indium impurities (which have three valence electrons) are used in combination with silicon, this creates a crystalline structure which has 'holes' in it, that is, places within the crystal where an electron would normally be found if the material was pure. These so called 'holes' make it easier to allow electrons to flow through the material with the application of a voltage. In this case, 'holes' are considered to be the charge carriers in this 'positively doped' conductor, which is referred to as 'P' material. Positive charge carriers are repelled by the positive pole of the DC supply and attracted to the negative pole; thus 'hole' current flows in a direction opposite to that of electron flow.

Figure 1.64 shows two dissimilar materials, one is N type and the other P type. It is important to note that the heat will be moved (or 'pumped') in the direction of charge carrier movement throughout the circuit (it is the charge carriers that transfer the heat). Thus the electrons flow continuously from the negative pole of the voltage supply, through the N pellet, through the copper tab junction, through the P pellet, and back to the positive terminal of the supply.

The positive charge carriers (i.e. 'holes') in the P material are repelled by the positive voltage potential and attracted by the negative pole and flow through the positive pole through the P pellet and copper tab to the N pellet and the negative terminal. When a DC current is applied heat is moved from one side of the device to the other – where it must be removed with a heat

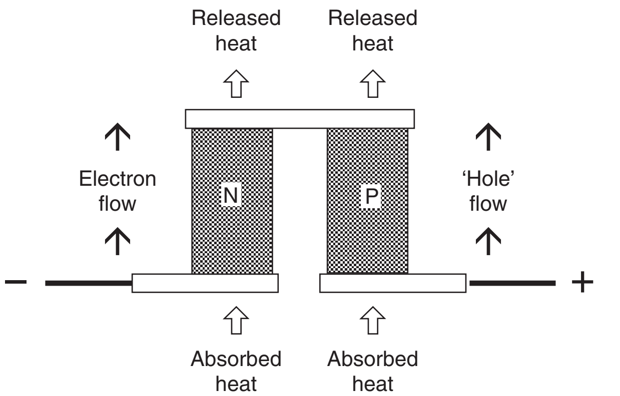


Figure 1.64 One simple semiconductor pellet (courtesy of Tulleride)

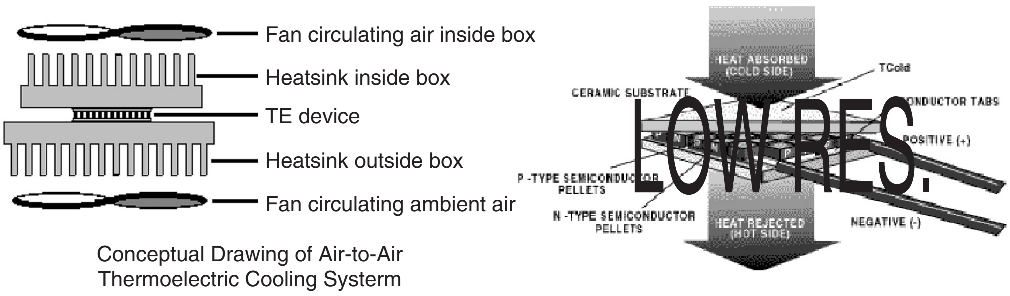


Figure 1.65 Peltier module (courtesy of Tulleride)

sink. The 'cold' side is commonly used to cool. If the current is reversed the device makes an excellent heater.

Arranging N and P type pellets in a 'couple' and forming a junction between them with a plated copper tab, it is possible to configure a series circuit which can keep all of the heat moving in the same direction. Using these special properties of the TE 'couple', it is possible to team many pellets together in rectangular arrays to create *practical* thermoelectric modules. These devices can pump appreciable amounts of heat, and with their series electrical connection, are suitable for commonly available DC power supplies. The most common TE modules in use connect 254 alternating P and N type pellets and use 12 to 16 VDC supply and draw 4 to 5 amps.

Thermoelectric modules look like small solid-state devices that can function as heat pumps. A 'typical' unit is a few millimetres square to a few centimetres square. It is a sandwich formed by two ceramic plates with an array of small bismuth telluride cubes ('couples') in between.

Heatsinks are used to either collect heat (in heating mode) or dissipate collected heat into another medium (air, water). Heat must be transferred from the object being cooled (or heated) to the Peltier module and heat must be transferred from the Peltier module to a heatsink. Systems are often designed for pumping heat from both liquids and solids. In the case of solids, they are usually mounted right on the TE device; liquids typically circulate through a heat exchanger (usually fabricated from an aluminium or copper block) which is attached to the Peltier unit. Occasionally, circulating liquids are also used on the hot side of TE cooling systems to effectively dissipate all of the heat.

Peltier device cooling and heating speeds can change temperatures extremely quickly, but to avoid damage from thermal expansion the rate of change is controlled to about 1°C per second. It is theoretically possible to get a temperature difference across a Peltier module of 75°C although it has been stated that in practice this is not achieved. In practice the results are about half this figure.

If a TE module is to be used to cool anywhere near freezing then water condensation must be considered. Ever-present water vapour begins to drop out of the air at the 'dew point'. This will result in the TE module, and what it is being used to cool, to get wet. Moisture inside of the TE module will cause corrosion and can result in a short-circuit. A solution to this problem is to operate the TE module in a vacuum (best) or a dry nitrogen atmosphere.

System control

Varying the power supply is often used. Pulse width modulation can be used, but a frequency above 2 kHz is recommended and the voltage applied must not exceed the recommended maximum voltage (T_{max}).

Peltier devices are best suited to smaller cooling applications. They can be stacked to achieve lower temperatures, but are not very 'efficient' as coolers due to the heating effect of the current flowing as well as drawing a great deal of current but act as very good heaters. This disadvantage can be offset by the advantages of no moving parts, no Freon refrigerant, no noise, no vibration, very small size, long life, and the capability of precision temperature control.

Automotive application – Amerigon's proprietary CCS system

Vehicle cabin air is drawn into the cushion and back TE modules and, based on inputs from individual seat controls and from temperature sensors, the unit will either add heat or remove heat to the air flow.

The basis of the system is the Peltier circuit. The Peltier circuit, heatsink (heat exchanger) and fan assembly are mounted as one module. Air is used as a medium to move heat around the seat through the perforated seat layers. Conditioned air is ported to the top surface of the foam through channels which evenly distribute the conditioned air over the surface. Breathable trim covers allow the conditioned air to pass through to the occupant. When the Peltier device is cooling, heat is generated on the opposite side of the device which must be removed to allow the temperature differential to exist.

This heat is pumped into the cabin space and is labelled on Figure 1.66 as 'waste heat'. This will create an extra load on the A/C system if being operated to cool the interior space.

When voltage is applied to the Peltier module in one direction one side of the Peltier device will be hot and the other cool due to the direction of the charge carriers creating a ΔT across the Peltier device. Switching polarity of the circuit creates the opposite effect.

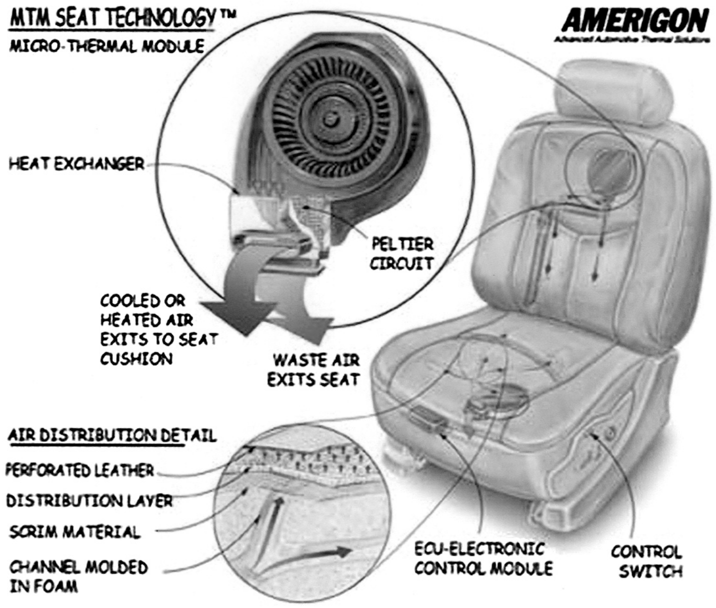


Figure 1.66 Amerigon's Peltier module CCS system (courtesy of Amerigon Corporation)

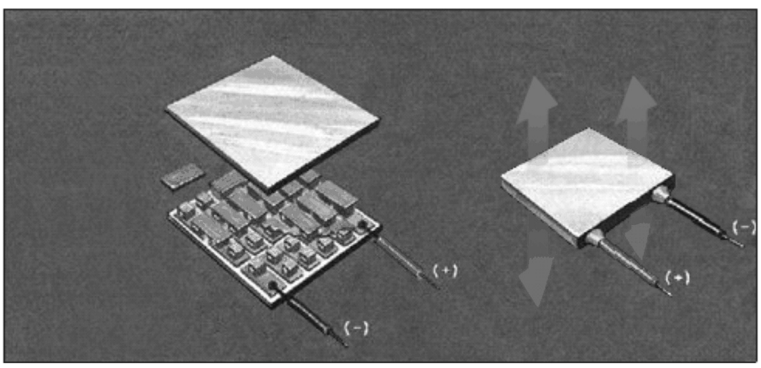


Figure 1.67 TE module showing Peltier couples and copper tabs stacked in series (courtesy of Amerigon Corporation)

Amerigon's Peltier module proprietary CCS system allows occupants to select seat temperatures to promote comfort and reduce driver fatigue through the use of a solid-state heat pump combined with an active, microprocessor controlled temperature management system to vary heating and cooling capacity.

Amerigon states that it is the first to have successfully packaged this technology for use in automotive seating applications.

1.6 The air-conditioning system

System activation

The signal to activate the air-conditioning system comes from the occupant(s). Activation is completed by the onboard Electronic Control Unit (ECU). The ECU has a number of inputs which send electronic signals based on sensed conditions, e.g. temperatures, pressures, speeds, positions. Based on this information the ECU will either activate or deactivate (if already operating) the system. If the system does not activate then a fault in the form of a code will be stored in the computer and on some systems a light will be activated to tell the driver a fault exists with the system. Advanced systems may use telematics to send a signal to a call centre who will advise the customer of the required action, i.e. urgency on visiting a dealership.

Activation of the air-conditioning system is achieved under some of the following conditions:

- The outside air temperature is above 9°C.
- The engine has been running for more than 5 seconds.
- The temperature of the evaporator is above 4°C (no ice forming over the surface).
- The engine coolant temperature is approximately between 40°C and 105°C.
- The vehicle is not rapidly accelerating or the engine is under high load (overtaking etc.).
- The air-conditioning activation button has been selected and the interior fan is on.

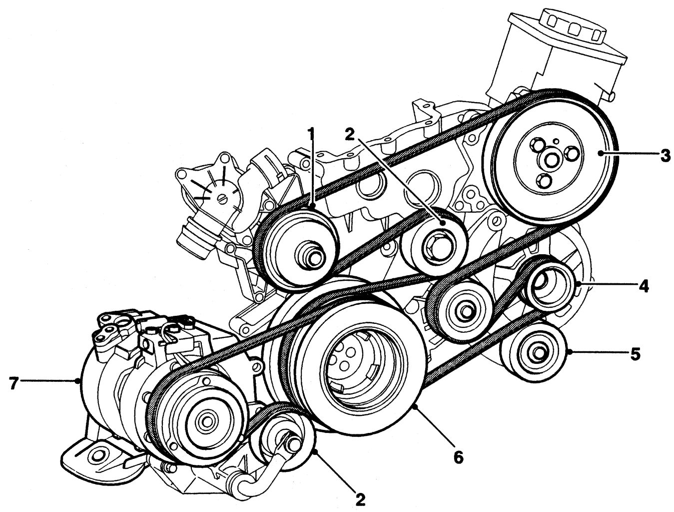


Figure 1.68 Compressor drive system (courtesy of Rover Group PLC)

- The sensors in the air-conditioning system have acknowledged that the system is under pressure assuming that a quantity of refrigerant exists inside the system and that it has not leaked out to the atmosphere (sensed by either pressure switches or sensors).
- No fault codes exist in the ECU.

Simple electronic circuit

Upon activation current flows from the vehicle battery through fuses, switches fitted to the A/C system and often an A/C relay to a magnetic clutch. The A/C relay is generally controlled by an onboard computer, which makes the ultimate decision to allow the A/C system to be activated based on system integrity, that is, the system has no faults and conditions are right for system activation. The clutch is positioned behind the compressor pulley and once activated will make a physical connection between the compressor pulley, which is driven by the engine, and the internal pumping elements.

1.7 The expansion valve system

The air-conditioning system works on a continuous cycle. A compressor receives low pressure heat laden refrigerant vapour from the evaporator. The compressor pressurises the refrigerant

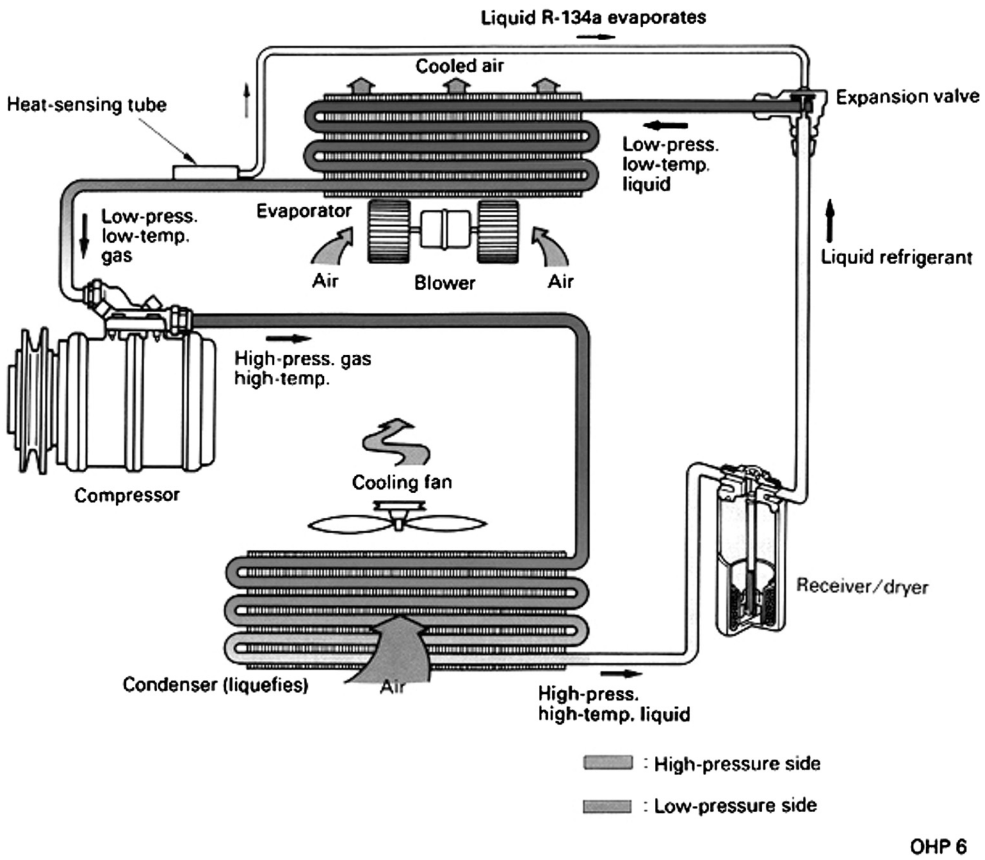


Figure 1.69 Expansion valve system – also reproduced in colour in the plate section (with the agreement of Toyota (GB) PLC)

from 30 psi to approximately 213 psi depending on system demand. This increases the temperature from approximately 0 to 80°C. At this temperature and pressure the refrigerant is above its boiling point of approximately 57°C. The compressor discharges superheated refrigerant vapour to the condenser.

The refrigerant flows into the condenser. The condenser has numerous cooling fins in which the vapour is pumped. In the condenser the high pressure vapour condenses into a high pressure liquid. This is achieved by reducing the temperature from, for example, 80°C to below 57°C which is the refrigerant's boiling point. This is achieved by forcing air over the surface of the condenser enabling heat to transfer from the refrigerant to the outside air thus reducing its temperature (subcooled). Only refrigerant in the form of a high pressure subcooled liquid leaves the bottom of the condenser outlet.

The subcooled liquid refrigerant flows into the receiver drier which stores, dries and filters the liquid refrigerant.

The subcooled liquid refrigerant then flows from the receiver drier to the expansion valve which then changes the refrigerant into low pressure low temperature liquid/vapour. This is achieved by lowering the pressure using a variable orifice. The orifice has high pressure one side (from the receiver drier) and low pressure the other (evaporator and compressor) and allows a small quantity of refrigerant to flow through it. The sudden drop in pressure and temperature causes some of the refrigerant to vaporise which is called a flash gas. The low pressure low temperature liquid/vapour then flows to the evaporator where the heat is transferred from its surface to the refrigerant through vaporisation. The heat comes from either inside (recycled air) or outside (fresh intake of air) the vehicle and is blown over the evaporator's surface. Once the refrigerant has completely vaporised and reached its saturation point it should still be able to carry more heat. The refrigerant continues to flow through the remainder of the evaporator coils absorbing more heat and becoming slightly superheated.

The low pressure low temperature slightly superheated vapour refrigerant flows to the compressor and the cycle repeats it self.

> *Note* – temperatures are approximate and are dependent on refrigerant type, system load, pressure and temperature relationship.

1.8 The fixed orifice valve system (cycling clutch orifice tube)

The air-conditioning system works on a continuous cycle. A compressor receives low pressure heat laden refrigerant vapour from the evaporator. The compressor pressurises the refrigerant from 30 psi to approximately 213 psi depending on system demand. This increases the temperature from approximately 0 to 80°C. At this temperature and pressure the refrigerant is above its boiling point of approximately 57°C. The compressor discharges superheated refrigerant vapour to the condenser.

The refrigerant flows into the condenser. The condenser has numerous cooling fins in which the vapour is pumped. In the condenser the high pressure vapour condenses into a high pressure liquid. This is achieved by reducing the temperature from, for example, 80°C to below 57°C which is the refrigerant's boiling point. This is achieved by forcing air over the surface of the condenser enabling heat to transfer from the refrigerant to the outside air thus reducing its temperature (subcooled). Only refrigerant in the form of a high pressure subcooled liquid leaves the bottom of the condenser outlet.

The liquid refrigerant then passes through a fixed orifice tube – a tube with a fixed cross-sectional area allowing only a metered quantity of liquid refrigerant to pass through it.

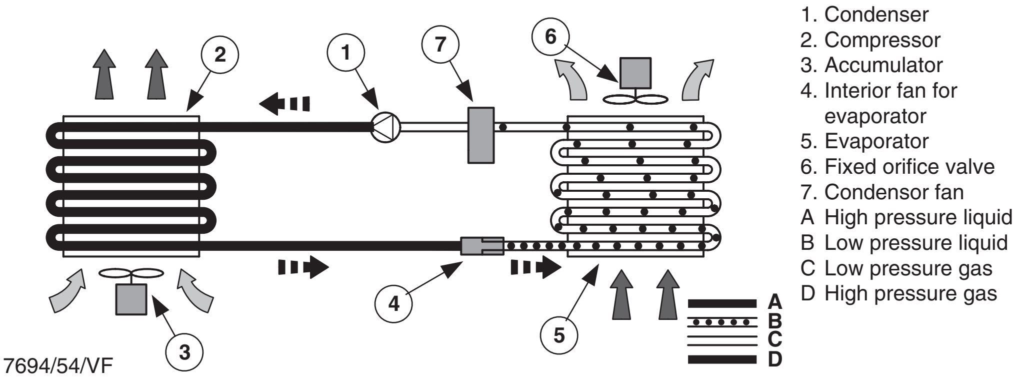


Figure 1.70 Fixed orifice valve system
(reproduced with the kind permission of Ford Motor Company Limited)

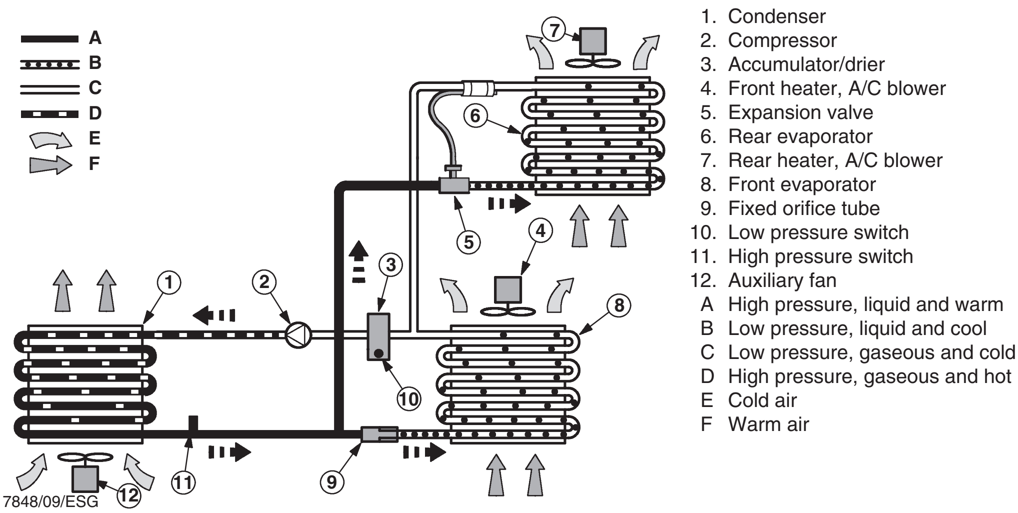
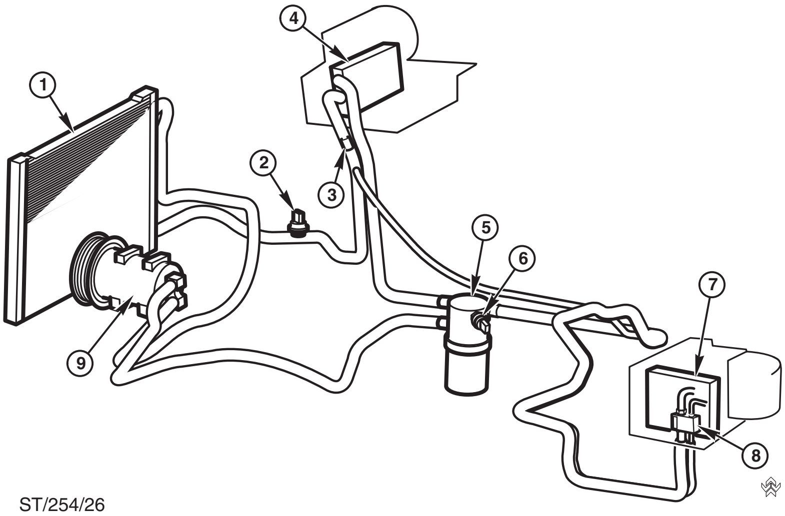


Figure 1.71 Dual air-conditioning system
(reproduced with the kind permission of Ford Motor Company Limited)

The low pressure low temperature liquid is then forced to expand rapidly due to the increase in volume of the evaporator. This drop in pressure causes the refrigerant to boil (vaporise) and absorb large amounts of heat energy which is transferred from the air flowing over the evaporator's fins to the evaporator's surface and thus to the refrigerant through vaporisation. After the heat is removed from the air it is directed to the vehicle's interior.

The low pressure low temperature liquid/vapour refrigerant flows from the evaporator to the top of the accumulator which acts as a drier and storage device and separates any liquid from vapour to protect the compressor (compressor can only pressurise vapour). The large surface area of the accumulator also assists in any final evaporation of liquid refrigerant. The saturated vapour and a tiny percentage of liquid refrigerant to carry oil from the oil bleed leave the accumulator from the top and flow under low pressure to the compressor (suction side) and the cycle repeats itself.



1. Condenser
2. High-pressure switch
3. Fixed orifice tulxe
4. Front evaporator
5. Suction accumulator/drier
6. Low-pressure switch
7. Rear evaporator
8. Expansion valve
9. Compressor

Figure 1.72 The components of a dual A/C system

Note – temperatures are approximate and are dependent on refrigerant type, system load, pressure and temperature relationship.

1.9 Dual air-conditioning

This system often combines the use of a fixed orifice valve and an expansion valve. The primary operation of the system shown in Figure 1.71 is a fixed orifice system with additional outlets and inlets which feed an additional expansion valve and evaporator to aid additional cooling. The additional cooling is often fitted in the back of a large multi-passenger vehicle given two temperature control zones – front zone and rear zone. The outlet (8) from the primary system to the additional expansion valve/evaporator is feed from the inlet (7) to the fixed orifice valve. Refrigerant splits and flows from the outlet of the primary system to an expansion valve and evaporator. Their function is identical to the normal expansion valve system. Refrigerant vapour flows from the evaporator in the secondary system to the accumulator (4) then (3) in the primary system. The accumulator ensures that hot liquid enters the compressor from both systems.