Chapter 10

Heating, ventilation and air conditioning of motor vehicles

Werner Gengenbach

10.1 Climate

The climate of a region usually means the typical atmospheric conditions and characteristics of the weather. Climate influences the quality of life and even the possibility of maintaining life at all. It comprises the following factors:

air temperature
air humidity
air circulation
radiation
air pressure
air ionization
partial pressure of oxygen
electrostatic fields
radioactivity

In addition to the broad definition of climate, we also speak of a climate on a small scale, such as the passenger compartment of a car. Much has been written about 'climate control' in buildings, living and working areas, and reference will be made to some of these studies, since there is very little literature available on climate control in cars. Nor is any work known on the physical effects of electrical phenomena. Therefore neither electrostatic fields nor ionized air is considered.

As the term 'climate control' implies, the climate is not only defined but is regulated to provide optimum comfort, though it is not possible to influence all climatic factors in a motor vehicle. In the main, air temperature, air humidity and speed of air flow can be changed.

Climate control enhances safety in traffic in two ways. It enables the driver to concentrate better, thus reducing the risk of an accident. Also, by directing the air flow properly, the car's windows can be kept free of moisture, thus guaranteeing good visibility.

10.2 Physical aspects of climate

Several investigators have studied comfort and climate in living and working areas, but their work cannot be applied unconditionally to the motor vehicle, where volume occupied and duration of occupancy are so different.

The climatic factors that particularly affect comfort are dealt with in the following sections.

10.2.1 Interior temperature

Figure 10.1 shows the suggestions of various authors for a comfortable car interior temperature. Stolz[10.21] suggests 26–30°C, regardless of ambient temperature, whereas Müllejans and Illg[10.16] recommend 25–33°C for an ambient temperature of −20°C. Veil[10.23] suggests an interior temperature of 22°C regardless of outside temperature, a value also recommended for motor vehicles by DIN 1946[10.4] in the range from −18 to +20°C.

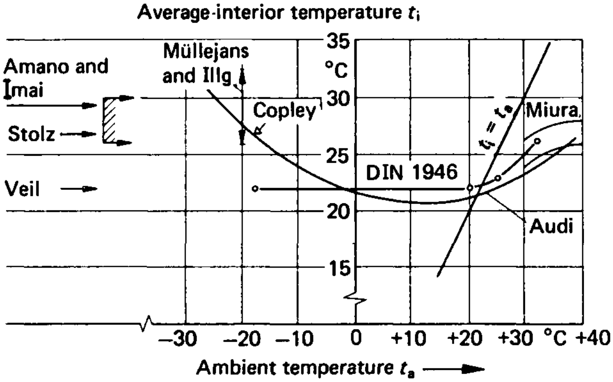

Figure 10.1 Specifications given in the literature concerning comfortable temperature in the interior of a motor vehicle, related to ambient temperature; compiled by J. Temming

In the author's opinion, the temperature range for comfort should be related to ambience. During winter one feels comfortable at a somewhat higher temperature than in summer. When the body is accustomed to very high outside temperatures, the temperature experienced as comfortable also rises. There are also medical reasons for raising the temperature of the interior; given for instance an ambient temperature of +40°C and an interior temperature of 22°C, the risk of cold infection is increased by the temperature difference.

The author's recommendation ('Audi' curve in Fig. 10.1) shows a rough range of temperature which is considered comfortable. Clothing, the time of day, state of health of the passengers, etc. will influence these figures, and it is important that the interior temperature can be finely adjusted over a wide range.

The data given in Fig. 10.1 are based on many years of experience. It will be noted that interior temperatures of motor vehicles are somewhat higher than for living or working areas. This is because the temperature of radiation from the walls of a building is considered the same as the room temperature, which is correct. In a motor vehicle, however, the relatively large glass areas may be cooler than the passenger compartment. Therefore the radiation from the windows has to be compensated for in winter by a higher interior temperature, the more so when the outside temperature—and consequently the temperature of the window surfaces—falls. In summer the opposite is the case. In cars with air conditioning the delivery of cold air has to compensate for the heat of the sun through the large, inclined glass areas typical of modern cars.

In buildings, it is sufficient to specify a standard temperature for the indoor space. In a motor vehicle, however, it is necessary to specify a difference in temperature between head and foot level, referred to as temperature stratification. Miura[10.15] describes tests on 50 individuals in a climatic chamber to determine the most comfortable temperature stratification. Figure 10.2 shows that a temperature difference of approximately 7°C between the foot and head areas was found to be the most comfortable.

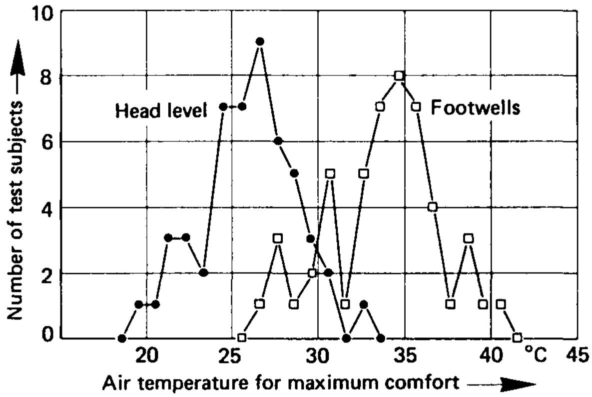

Figure 10.2 Statistical investigation to find the most comfortable temperatures in foot and head areas inside a motor vehicle, after ref. 10.15

Similar figures can be found in other literature dealing specifically with temperature distribution in motor vehicles. None of these articles mentions the sources used, so it can be taken that they are the result of extensive experience of engineers from the automotive industry concerned with heating and climate control.

Figure 10.2 shows clearly the wide range of temperatures found comfortable by various persons under the same conditions. Differences of up to 14°C were recorded for the foot wells as well as for the head area.

The results referred to so far indicate comfortable temperatures in the steady-state condition. Tests involving 3000 people carried out by Rohles and Wallis[10.19] established that the time necessary to reach a comfortable temperature after switching on the air-conditioning unit in a car left standing in the sun depends only on the air delivery rate, the temperature of the cooled air and the seating position (front or rear). With a constant air delivery rate, the size of the outlets and therefore the air speed are of no importance.

The conditions for heating-up are much more complex, as the passengers' response is masked by the warm-up phase of the engine, etc.

10.2.2 Air speed

It is well known that people experience the temperature of still air differently from that of moving air. When the ambient temperature is lower than skin temperature, the temperature has to be raised with increasing air speed to give the same subjective feeling of temperature as in still air. The literature is divided regarding the relationship involved. Figure 10.3 shows a compilation by Temming of data from the literature (refs 10.4, 10.7, 10.13, 10.14, 10.22). Notably, the graph by Fanger[10.7] shows the existence of a temperature limit where the subjective feeling of temperature no longer changes even if air speed is increased above about 1.5 m/s. This is in accordance with practical observations, at least as far as qualitative results are concerned.

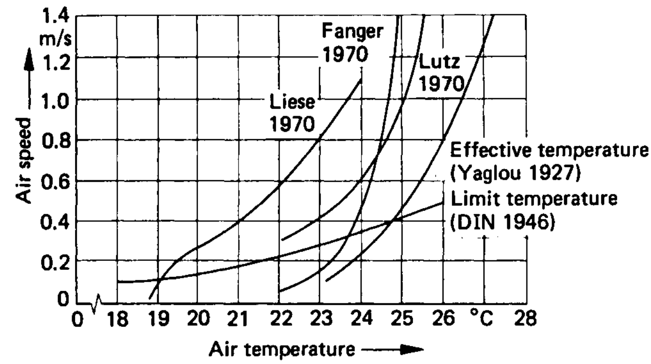

Figure 10.3 Influence of air speed (air flow directed at occupants) on subjective feeling of temperature. Comparison of publications by various authors; compiled by J. Temming

When the air temperature exceeds the skin temperature, as in hot desert areas, the gradient of the graph is reversed, i.e. the moving air feels hotter than still air. Therefore, when driving without air conditioning in temperatures above 40°C all windows and all air outlets should be closed.

Similarly, when heating the passenger compartment a direct air stream onto the passengers should always be avoided. The outlets for heated air therefore require very careful location and an optimally directed air flow, regardless of air delivery rates.

In summer, however, at higher ambient temperatures, a direct air stream to the body enhances comfort. It is best to direct the flow to the chest area at an air speed of up to 3 m/s, but the throat and uncovered wrists should not be subjected to a direct air flow due to the risk of cold infection. The face, too, and especially the eyes, must be protected from faster air flows. For medical reasons, high air speeds should be avoided completely, even though they bring about a local feeling of intensive cooling. It is preferable to direct large quantities of air towards the passengers over a wide area. When outside temperatures are low or when air conditioning is used, it should be possible to introduce slightly warmed-up air (reheat system with completely integrated air conditioning).

Today, this knowledge is widely utilized in every modern car equipped with different air outlets for heating and ventilation. It should be possible to adjust the outlets individually for air delivery and direction.

10.2.3 Air humidity

The control mechanism that stabilizes the temperature of the human body at approximately 37°C uses, amongst other things, the latent heat of evaporation of perspiration on the surface of the skin. Even in neutral thermal conditions, the human body releases perspiration at the rate of about 25 g per hour. This quantity increases as surrounding temperature rises. The evaporation of moisture on the skin surface and thus the feeling of comfort depends of course on the vapour pressure of the surroundings and thus on the relative humidity of the ambient air. It is not easy to stipulate exact limits of conditions still felt to be comfortable, or which may become uncomfortable, for many factors have a large influence, e.g. solar radiation, physical stress and minor day-to-day health variations, etc.

The literature very often indicates a water vapour pressure of 1.87×10^3 Pa as the limit where conditions are felt to be 'close', or oppressive. This water vapour pressure results in a relative humidity of

80 per cent at an ambient temperature of 20°C
60 per cent at an ambient temperature of 25°C
45 per cent at an ambient temperature of 30°C

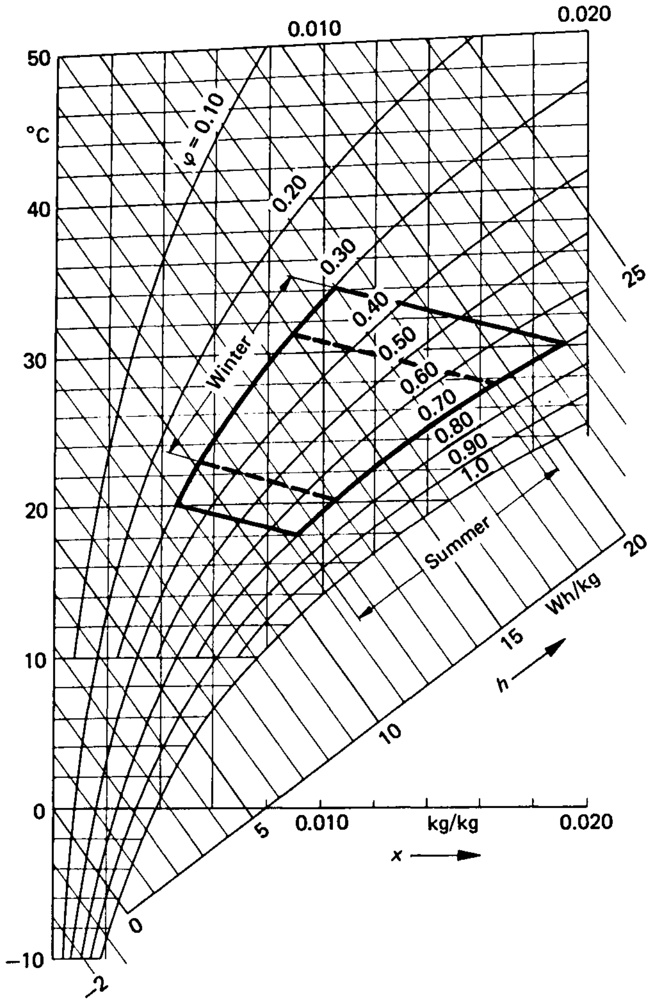

Figure 10.4 Comfort ranges in *h*-*x* graph, distinguished for summer and winter

When these limits of humidity are exceeded, the only way of preventing the atmosphere becoming oppressive is to dry the air in the vehicle by means of an air-conditioning system.

On the other hand, air that is too dry is not necessarily uncomfortable, although health can be impaired due to the higher infection risk, rough skin, chapped lips, etc. In such cases the air in fully air-conditioned buildings is humidified artificially. No such conditions are known for motor vehicles, especially since there is no source of data for the relatively short periods spent travelling in vehicles with extremely dry air.

Comfort at varying temperatures and humidity conditions is shown in the *h-x* graph (Fig. 10.4), which also distinguishes summer and winter operation.

10.2.4 Requirements for climate control in motor vehicles

The requirements for a comfortable climate in a motor vehicle can be summarized as follows:

- Temperature must be adjustable over a wide range; fine adjustment is important.
- Temperature should vary as little as possible during driving.
- Warm air should not be blown directly onto the passengers.
- Headroom should be about 7°C cooler than the footwells (temperature stratification).
- Relative air humidity should be between 30 and 70 per cent.
- It must be possible to direct ventilating air towards the occupants at the required temperature. Direction and air delivery must be adjustable. The air flow to the body should cover a large area at not too high a speed. Air speed should be low on the face, neck and wrists.

10.3 How climate can be influenced

Figure 10.5 shows two examples of how the climate in the passenger compartment can be influenced when the interior is heated. The first example assumes a foggy day at an ambient temperature of about 10°C with 100 per cent relative humidity; the air must be heated to about 45°C in the heater so as to obtain a mean temperature of about 25°C in the vehicle. Assuming that 2 g of water per kilogram of air are absorbed from the moist air exhaled by the passengers and possibly from damp clothing, the resulting humidity is about 45 per cent, which is still within the range of comfort.

The second example assumes that air is heated from −10°C with 100 per cent relative humidity up to about 28°C in the interior. Here, too, we can take it that 1 kg of air entering the car absorbs about 2 g of water. The result is a relative humidity of 16 per cent, which means that the air is too dry. The possibility of chapped skin and the increased infection risk have already been pointed out.

At high outside temperatures and air humidity levels, ventilation alone cannot produce a comfortable climate in the car. However, in this case the

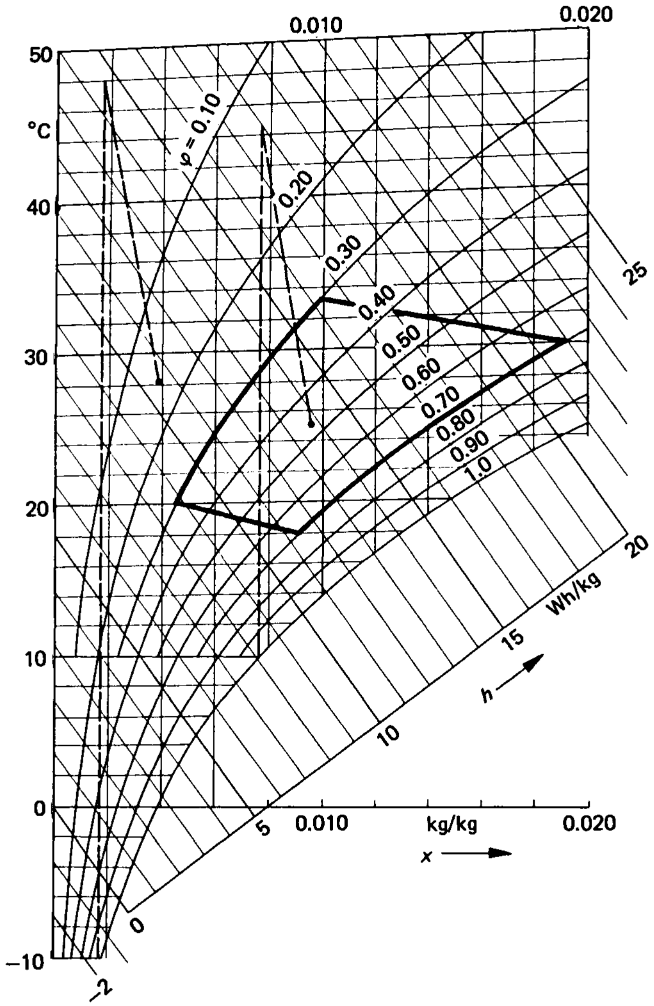

Figure 10.5 Effect on variables when air is heated to warm car interior: (a) at 10°C with saturated air; (b) at −10°C with saturated air

installation of air conditioning can be of considerable advantage. Figure 10.6 shows the changes in variables when air conditioning is used. Fresh air operation is assumed, with outside temperature 40°C and a relative air humidity of about 30 per cent. Such climatic conditions prevail for instance in Colorado, USA, and are very uncomfortable and oppressive.

The air entering the air conditioner is cooled to about 8°C by the evaporator. Here, about 7 g of water are lost for each kilogram of air fed into the compartment. The resulting interior temperature of about 27°C results in a relative humidity of 40 per cent, again assuming that about 2 g of water are absorbed per kilogram of air. Thus the conditions obtained are within the range of comfort. It is obvious that the cooling effect of the air conditioner is all taken up in condensing the water and thus is no longer available for cooling the air.

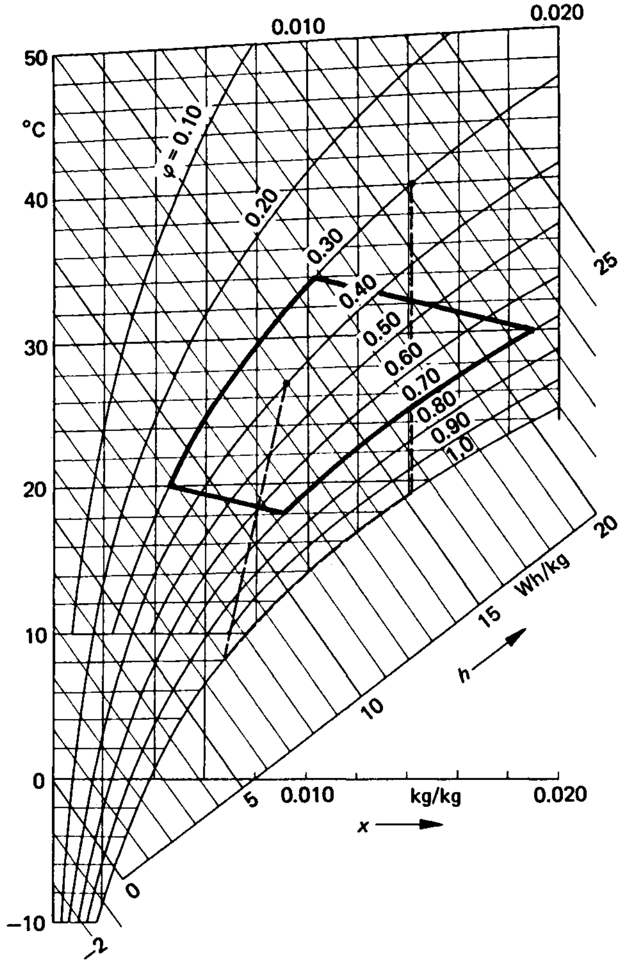

Figure 10.6 Effect on variables when air is cooled by air conditioner. Ambient air: 40°C and 30 per cent relative humidity

These examples show that, especially when only heating and ventilation are employed, climate control in the vehicle interior is not possible to the full extent desirable. Only the temperature of the air can be so influenced, and then only by heating. The resulting relative drying effect cannot be avoided. At outside temperatures only slightly above the comfort range, air directed towards the passengers over as wide an area as possible will restore comfort. Excessive air humidity cannot be influenced.

Only by installing an integrated air conditioner (or refrigeration system) can the climate in the vehicle be influenced further, and the uncomfortable air humidity at higher temperatures be reduced. Furthermore, the temperature in the vehicle can be lowered as well as raised in relation to the outside temperature.

10.4 Components of a heating and ventilation system

Climate control in the passenger compartment is usually effected by means of a heating and ventilation system, with which every modern vehicle is equipped. Greater demands for climate control can only be satisfied by an air conditioner. Although air conditioning does not fall within the scope of this chapter the comments on heating can basically be applied to air conditioning if the state of the air fed to the heater is altered accordingly, i.e. if the temperature is lowered and (as in most cases) if the air is saturated with water vapour.

The main components of a heating and ventilation system are: car body, heat exchanger, fan, and controls.

10.4.1 Car body

The requirements for producing a volume flow are a pressure difference and an open area allowing through flow. Firstly, the pressure difference provided by the fan itself is used for producing an air flow, and secondly the body itself plays a most important part. (See also sections 2.3.2, 6.2.2 and 12.3.3.1.)

By reason of its design the passenger compartment of a vehicle can never be quite airtight. There are always air leaks at weatherstrips, window frames, welding flanges, grommet holes, etc. through which the air in the passenger compartment can be exchanged with the outside air. Following the definition in section 12.3.3, the cross-sectional area of these leakage points can be determined relatively easily by blowing air into the interior by means of a test fan with an airtight duct and flow measuring equipment, and by recording the amount of air leakage in relation to the pressure in the passenger compartment. Having obtained this graph, we can assume the same flow rate through a nozzle with an area A_e, working without loss. This area can be taken as the effective cross-sectional area passed through by the air leaking out of the body (like an 'equivalent nozzle'). The advantage of this procedure in comparison with other methods is that the

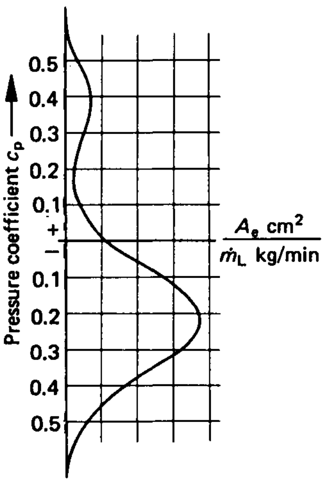

Figure 10.7 Distribution of equivalent leakage cross-sectional areas related to the pressure coefficient at closed air outlets of the cabin. (The author thanks Dipl.-Ing. Holger Grossmann, Audi AG Ingolstadt, for kindly letting him have this so-far unpublished material)

leakage area is represented clearly and simply, and if there is any alteration the change can be directly added or subtracted.

The air flow around a moving vehicle gives rise to high pressure areas at points where the air flow is retarded, and low pressure areas at points where the flow is accelerated, as shown in section 2.3.2. The air leaks from the body described above are distributed at various positions on the vehicle, so the pressure coefficient for the various leakage points will also be different. Generally, this results in a distribution curve which is characteristic for a particular vehicle, but which does not differ greatly from vehicle to vehicle. Figure 10.7 shows a distribution curve of this kind. The equivalent cross-sectional area is shown as a distribution related to the effective pressure coefficient c_p. The resulting leakage air flow can be derived from the sum of the individual leakage cross-sectional areas with the appropriate pressure drop.

As can be concluded from Fig. 10.7 the leaks are generally concentrated at locations where the pressure is below ambient ($c_p < 0$), whereas the air intake is always at a position of pressure higher than ambient ($c_p > 0$). This explains why even cars with no special provision for air extraction have a through flow of air. Its mass flow can be calculated from Eqns 2.50 and 2.51.

The random leakage areas of a body shell depend largely on the quality in production. It has therefore been general practice for several years not to leave air extraction from the passenger compartment to chance, but to provide extraction apertures for the purpose. The intensity of the low pressure area at the extraction aperture location enables the air flow through the compartment to be related to road speed with a steeper or flatter gradient. If a point with slight negative pressure is chosen with an appropriately large cross-sectional area, the air flow does not vary greatly with road speed; if a position is chosen with greater negative pressure, the air flow rises sharply as road speed increases. The best arrangement appears to be one where air flow does not vary greatly with road speed, and where high air flow rates are obtained at low road speeds and when the vehicle is stationary.

In practice it is difficult and time-consuming to determine the individual leakage cross-sections and the appropriate pressure coefficients. A practical method is to measure the air extraction characteristics of the vehicle by blanking off the extraction vents and determining the air flow with a test blower in relation to the interior pressure in the vehicle, see section 12.3.3. It is now possible to determine the extraction curve for the leakage areas and the extraction openings together, either mathematically or by measurement, both for the stationary vehicle and for a constant road speed. A diagram of this kind is shown schematically in Fig. 10.8. The diagram also shows the characteristics of the incoming air flow, which are partly determined by the characteristics of the heater fan employed. Operation without the fan, using ram air only, is also represented. The points of intersection of the curves give information concerning the air flow and how this varies with road speed.

This technique provides useful information about air flow at an early stage of development, and makes it possible to optimize the position and effectiveness of the extractor vents on the car. For this purpose it is

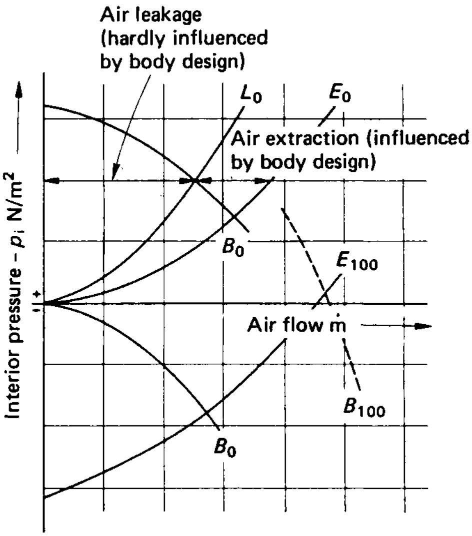

Figure 10.8 Characteristic curves for ventilation air intake and extraction from the vehicle interior, and—at intersections—determination of air throughput; index 0, speed $V = 0$, index 100, speed $V = 100$ km/h (62.5 mile/h)

necessary to know the equivalent leakage area A_e, for which data of sufficient accuracy are usually available from the previous model, or which can at least be estimated if the design of the body shell is changed. It is also necessary to know the pressure distribution on the external surfaces from wind tunnel tests with models, see Fig. 6.10.

10.4.2 Heat exchanger

The heat exchanger in a vehicle heating system is of special importance, as it not only has to provide the required amount of heat for warming up the passenger compartment, but is also to a large extent responsible for the function of the heating in maintaining an even and constant temperature.

Only a few years ago it was normal practice to construct heat exchangers similar to car radiators, see section 9.4.2. They consisted, for example, of flat tubing made of brass with copper or steel fins between the tubing. The tubes ended at each side in base plates enclosed in water chambers. The whole heat exchanger was soldered in one operation by passing it through an oven. Usually, the inlet and outlet connections were both in the same water chamber; the water flow was routed so that with the two-row heat exchangers the water flow in the upper row was supplied in reverse direction to the lower row. A partition in one of the water chambers prevented a short circuit.

Heat exchangers are nowadays frequently made of round aluminium tubing (see Fig. 10.9), which is much cheaper because no soldering is necessary. The aluminium tubing of about 0.4 or 0.5 mm wall thickness is assembled with the stamped air fins and then expanded with a mandrel. In this way, the close contact between the air fins and the tubing carrying the water is achieved by direct metal-to-metal contact, and not as with a

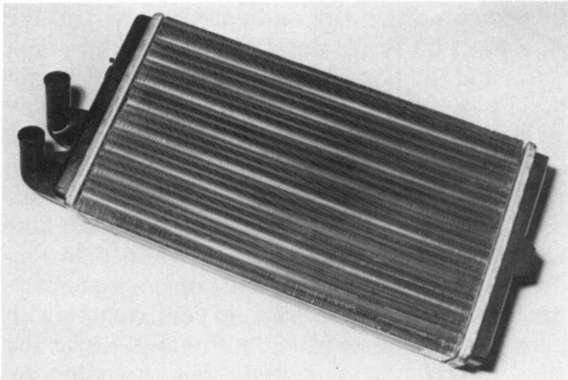

Figure 10.9 Modern aluminium heat exchanger with round aluminium tubing: surface of pipe matrix 42.6 cm^2, depth 42 mm

conventional heat exchanger by solder, which has poor heat conductivity. The disadvantage of round tubing over flat tubing, the reduced turbulence at the water-carrying surface, can be compensated for either by specially shaped turbulators or by using multiple passes on the water side to give higher water flow speeds. The sealing of the tubing in the base plates is achieved either with rubber seals or by metal contact with the aluminium tubing pressed into the base plate. The plastic water chambers are injection mouldings, sealed to the base plates with a rubber seal. The joint is effected by flanging the edges of the base plates. The routing of the water circuits is virtually unrestricted since partitions can be located in the injection moulded water chambers as required. Many car manufacturers nowaday use the same construction for their radiators as well; see section 9.3.2.

Figure 10.10 shows the characteristic curve of this kind of heat exchanger. On the left-hand side the heat flow $\dot{Q}_{100}$ (for a 100°C

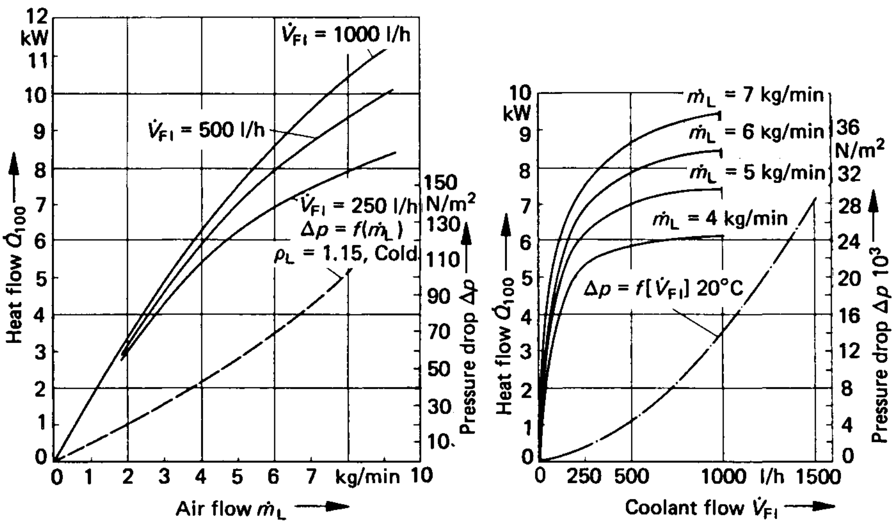

Figure 10.10 Characteristic curve showing heat flow of a heat exchanger

temperature difference between entering water and entering air) and the air resistance are shown as a function of air flow. The right-hand graph again shows the heat flow $\dot{Q}_{100}$ and the flow resistance in the water circuit as a function of water flow. The two graphs comprise all the data needed for the development of the heat exchanger and heating system design; a similar representation in dimensionless form for a car radiator is shown in Fig. 9.16. Different driving conditions are characterized by particular air and water flow rates, so it is possible to determine the attainable heat flow for any driving condition. This diagram is referred to again below in different form when describing possible regulating and control systems.

However, one such system is mentioned here since, in combination with the heat exchanger, there are certain effects which are important for the design and development of a vehicle heating system. This concerns the control of the heat flow by altering the water flow with a control valve. At maximum heat output, i.e. maximum water flow, the water remains at virtually the same temperature when passing through the heat exchanger, so that with a uniform air flow through the heat exchanger (the same air speed at all points in the heat exchanger), a uniform temperature distribution can also be expected downstream of the heat exchanger.

The situation is different when the heat requirement is low, i.e. with a small water flow. In this case the water does not remain at constant temperature when it passes through, but cools down noticeably. So with a uniform air velocity, the temperature distribution downstream of the heat exchanger will no longer be uniform. The air is warmer in the area where the water enters the heat exchanger.

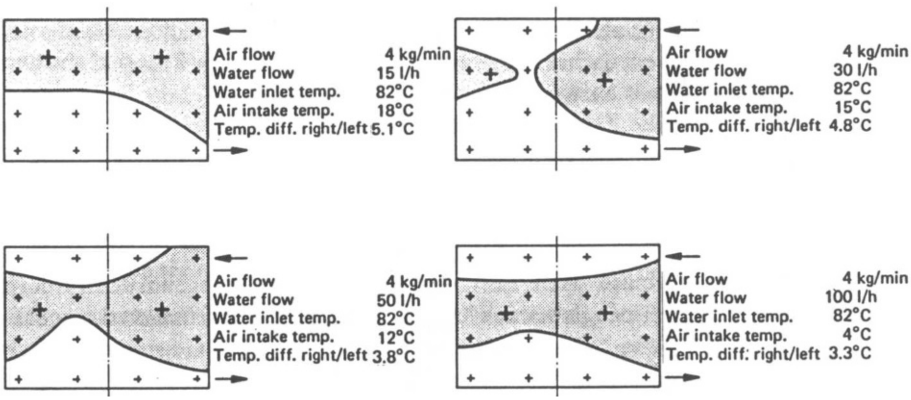

Figure 10.11 Temperature distribution and temperature difference between left and right halves of a heat exchanger with stratified flow and low liquid flow rate

Figure 10.11 shows four operating points of a heat exchanger with low water flow. The diagram is a view of the heat exchanger surface looking in the direction of the air flow. In all cases the air flow rate was a constant 4 kg/min. The temperature of the incoming air is chosen so that in all four cases the average interior temperature obtained is 25°C. Water flow rate is raised in steps from 15 to 100 litres per hour and the temperature of the water intake is a constant 82°C. The two-row heat exchanger is made of round aluminium tubing with turbulators and a stratified flow, i.e. the water in the rear row of pipes, as seen in the diagram, flows from right to left, and the water in the front row flows in the opposite direction.

The temperature of the air leaving the heat exchanger is measured with a grid of 16 thermocouples. The examples show the line of the mean outlet temperature. Areas with temperatures above the mean value are shaded and marked '+'. The maximum temperature difference of the air leaving the two halves of the heat exchanger is shown for each diagram.

At the very low water flow rate of 15 l/h = 0.25 l/min the temperature difference in this example is only about 5°C between the left and right halves. The temperature is higher on the water inlet side. With increasing water flow rates the difference in temperature becomes smaller.

A difference in the air temperature between the left and right side outlets of about 5°C will not be noticed by the passengers, because the heater outlet air will be mixed with the air of the cabin and so the average air temperature of the left and right side of the cabin will differ only very little. However, there exists the possibility of heating up the non-driver side of a car a little more than the driver's side, as recommended by some specialists in car-climatization. This is because the driver is in action and his body produces more heat than that of his passenger.

With a uniform air velocity, the temperature difference between various points on the surface of the heat exchanger can be influenced considerably by the routing of the water circuit, in this example a stratified flow. Apart from the water routing, the distribution of the air velocity also significantly influences the uniformity of the outgoing air temperature. A high air speed results in a low outgoing air temperature, and vice versa. Thus it is possible when developing a vehicle heating system to obtain an even temperature distribution at the heater outlets, even at low and very low water flow rates, by suitable routing of the water flow and distribution of the air velocity over the heat exchanger surface.

10.4.3 Fan

Both axial and radial (centrifugal) fans are used to produce the air flow for vehicle heating and ventilation. Axial fans are simpler and more robust than radial fans, but more noisy in operation. With increasing standards of comfort there is at present a clear tendency in favour of the quieter but more complex and expensive radial fan.

Figure 10.12 shows the characteristic curves for an axial and a radial fan. The design of both fans is such that they provide the same air flow operating with the vehicle stationary (point of intersection with the resistance curve). The characteristic difference between the two types of fan is clearly to be seen. Back pressure Δp varies only moderately with air flow $\dot{m}$ for the axial fan, but considerably for the radial fan, i.e. the axial fan is able to deliver large quantities of air with a low back pressure, and that air delivery is reduced sharply when back pressure increases by only a slight amount. The radial fan, on the other hand, is still able to deliver large quantities of air even with increasing back pressure. The diagram also shows that with the additional effect of ram pressure with the vehicle

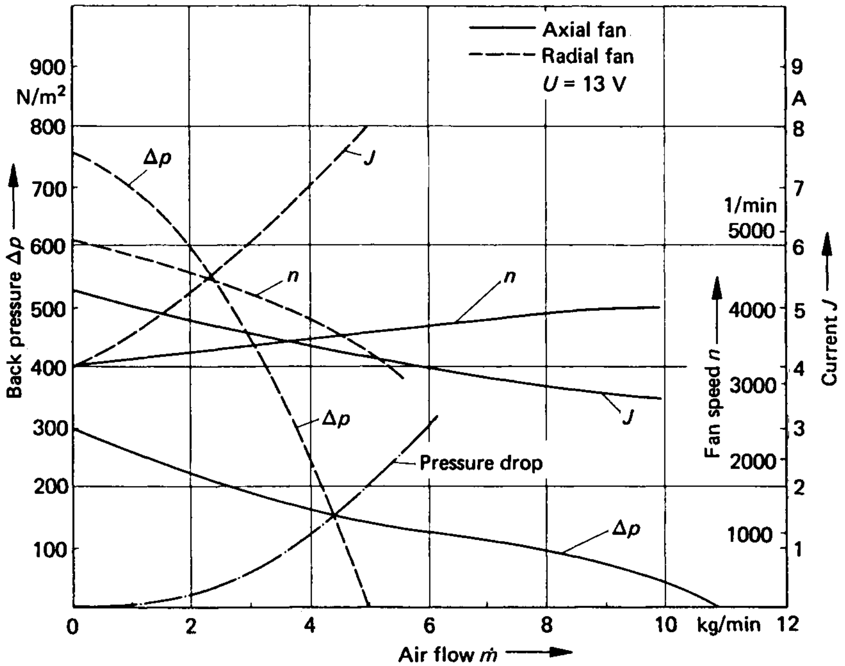

Figure 10.12 Characteristic curves of axial and radial fans set up to produce the same air flow with the vehicle stationary

moving, air delivery increases much less with the radial fan than with the axial fan.

The two types of fan differ in current consumption. The speed of rotation of the axial fan increases as the back pressure drops, and current consumption decreases. The opposite is the case with the radial fan, where the speed of rotation decreases with rising current consumption. This means that special attention must be paid to the thermal load on the motor of a radial fan running without resistance from back pressure. The motor must be designed to withstand long periods of driving at maximum speed, possibly with an open sun roof, and the fan at the fastest setting. It may be necessary to provide special air cooling for the motor. In some cases, thermal safety circuits may be provided to protect the motor when the fan is running without back pressure.

10.4.4 Temperature control

When developing a vehicle heating system, particular emphasis must be placed on the control of the heater output and thus of the average temperature in the vehicle interior. An effort must be made to obtain a fine temperature adjustment; once set, the temperature should preferably remain stable, even under widely varying driving conditions. When describing the characteristics of the heat exchanger it was shown that these are very much non-linear, so that variations in water flow (i.e. changing road speed in different gears) and air flow (dependent again on road speed and the fan setting) can have a great effect on the air temperature at the heater outlet and thus inside the compartment.

Two different systems are mainly used for temperature control. In *water-flow controlled heating*, as already described, the amount of water passing through the heat exchanger is restricted to a greater or lesser extent by a water flow control valve, according to the heat requirement.

This valve is normally operated from the vehicle interior via a Bowden cable. The regulating characteristics of this valve must meet very stringent requirements, as can be seen from Fig. 10.13, which shows water flow as a function of valve operating travel, as is required for fine control, i.e. linear temperature rise in relation to the operating travel.

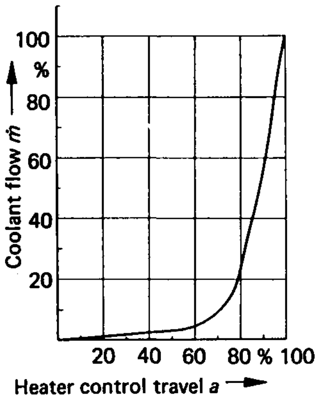

Figure 10.13 Required water flow rate through heat exchanger to obtain a linear temperature increase with the operating travel of heater control

Up to about 70 per cent of its operating travel the valve must restrict water flow to only about 10 per cent of the maximum flow rate through the heat exchanger. Over the last part of the operating travel the water flow must then rise steeply up to the maximum value. The difficulties of achieving this lie not only in the geometry of the valve, but also particularly in the fact that only a very tiny gap must be opened for such small water flow rates, and this gap can easily be obstructed by impurities in the cooling system. One possible design for such a valve is a quadrant plate gate valve. This employs a control plate as a sliding regulator which, in the version proposed by the author, has wedge-shaped slots to control the cross-sectional area of the opening for small water flow rates.

Figure 10.14 is a schematic diagram of a gate valve of this kind. The relative position of the circular regulator opening is shown for five different settings. In the first setting the regulator opening is completely covered and the valve is closed. In the second setting a small quantity of water can flow through the opening exposed by the slots. The steep rise in the flow characteristics starts in the third position where the crescent-shaped opening is exposed. The valve is fully open in position 5.

The second method of temperature control uses *air-flow controlled heating*, in which the unrestricted water flow, dependent only on the engine speed, passes through the heat exchanger at all times.

The required outlet temperature is adjusted by mixing cold and warm partial air flows. The amounts of air passing through or bypassing the heat exchanger are normally controlled via two temperature mixing flaps, one

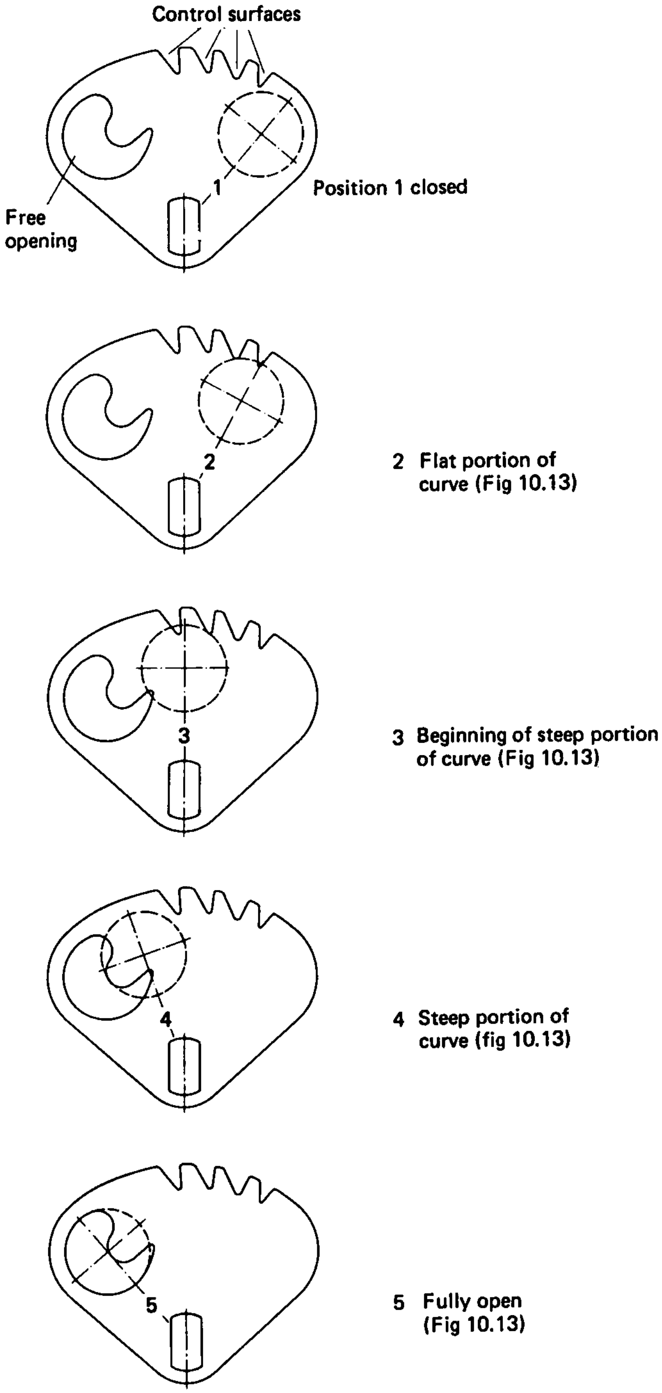

Figure 10.14 Principle of a quadrant plate gate valve for regulating the heater of a passenger car

upstream and the other downstream of the heat exchanger. Theoretically, one mixing flap upstream of the heat exchanger would be sufficient, but then turbulence and convection currents in the area downstream of the heat exchanger would always permit the addition of undesired warm air, even with the warm air flap closed. This would mean that even at the 'cold' setting, the air would still be noticeably warmed as it passes through the heater. With the arrangement employing two temperature control flaps in the Audi 100 II, the residual heating effect in the heating system at the 'cold' setting is below 2°C, even with low air flow rates. The temperature mixing flaps are controlled via a Bowden cable from the passenger compartment.

Apart from these two control systems, there are also mixed systems which work with a bypass duct as well as a water valve, as for example the Audi 100 I.

The two types of temperature control in the passenger compartment are discussed by Frank.[10.8] The advantages and disadvantages of the two systems can be explained with the aid of Fig. 10.15.

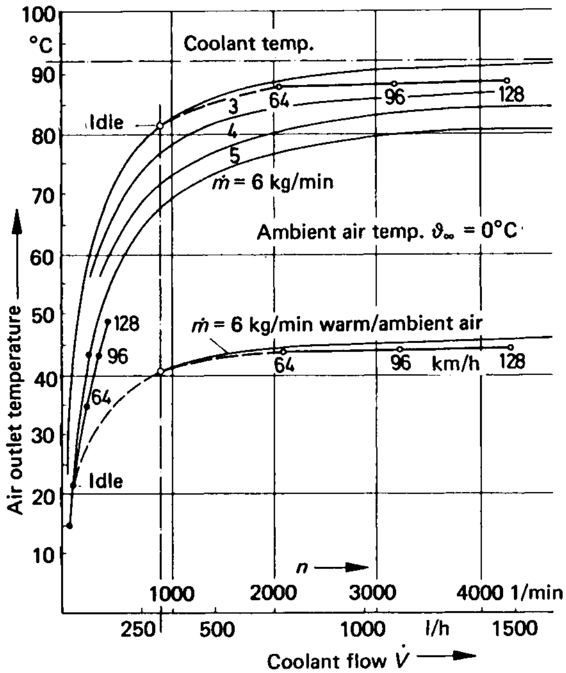

Figure 10.15 The air outlet temperature from a heat exchanger as a function of water and air flow

In this graph the temperature of the air leaving the heat exchanger is plotted against the water flow (which is proportional to engine speed) for different air delivery rates. The example assumes an ambient temperature of 0°C, and water supplied at a temperature of 92°C. Air delivery when stationary should be about 5 m^3/min = 6 kg/min, which is about twice the required fresh air delivery rate of 0.5 m^2 per person per minute for a car with five occupants. In order to achieve a comfortable interior temperature under the assumed conditions, approximately half the air flow is routed through the heat exchanger. This means that with the vehicle stationary about 3 kg/min pass through the heat exchanger. The air flow and the corresponding water flow are shown as open circles in the diagram for road speeds of 64, 96 and 128 km/h (40, 60 and 80 mile/h respectively) in 4th gear. It can be seen that the air outlet temperature at 64 km/h (40 mile/h) is just under 1°C higher than the temperature at 128 km/h (80 mile/h). This difference is halved since the hot air, heated to about 87°C, is mixed with the same quantity of air at 0°C, so the temperature fluctuation drops to about 0.5°C.

It can also be seen that the maximum temperature difference between the driving modes mentioned above and the idle condition is about 4.5°C in the outlet temperature from the heater. This means that the mean interior temperature will only vary by about 2°C, a value which is on the limit of perceptible temperature difference.

If the same heater system were controlled by restricting water flow, and if, for example, it is assumed that at 96 km/h (60 mile/h) the same air outlet temperature of about 43°C is achieved as in the case of the air-flow controlled heater, then the temperature at 128 km/h (80 mile/h) rises to about 48°C, and falls to 35°C at 64 km/h (40 mile/h), and to as low as 22°C at idle. The effect on the interior temperature of these temperature variations between idling and the various driving modes is that the temperature setting has to be altered if road speed is changed for any period of time. Short speed changes, as for example during overtaking, cause no perceptible temperature difference due to the heat capacity of the heat exchanger and the associated response delay of the system, so it is not necessary to readjust the temperature controls.

At lower air delivery rates (this example deliberately assumes a high air delivery rate) the temperature variations are also smaller. The same applies as the heater output is increased, when the points for the different driving modes are no longer on the steep section of the heat exchanger characteristic curve. At maximum heat output there is no difference between the two systems.

A further advantage of the air-flow controlled heater system is its fast response to a new setting. The occupants notice the change in temperature more quickly than with the slower response of the water-flow controlled system, and are therefore able to find a comfortable setting more quickly. For the same reason it is easier to make temperature adjustments with air-flow controlled heater systems than with water-flow controlled systems, which respond more slowly and are subject to much greater variations in the outlet temperature.

10.5 Example of a production heating system

Recent developments in the engineering of passenger car heating systems can be seen from the example of the Audi 100 II. Bauer[10.3] has described the heating system of the Audi 100 I (1969 model). It is intended here to describe the system used in the Audi 100 II, which is a further development of this design. Very much the same system was applied for the Audi 100 III (1982 model).

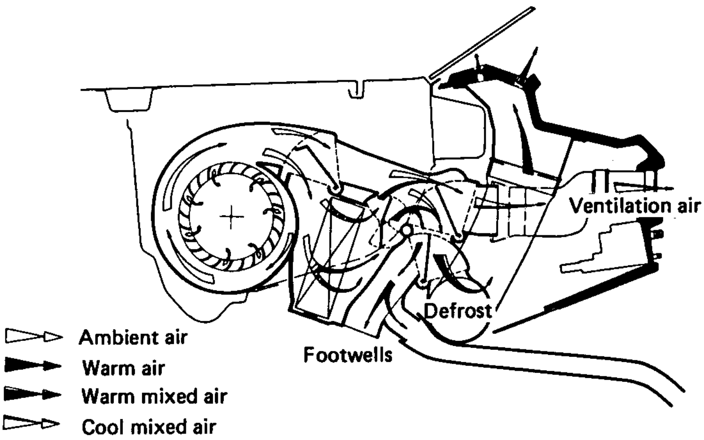

Figure 10.16 Audi 100 II heating system (1978 model)

Figure 10.16 shows a cross-section of the Audi 100 II heater, and also illustrates connection to defroster ducts, ventilation outlets and heater ducts for the rear passengers. The heater is arranged symmetrically about the centre line of the vehicle, with the exception of the blower intake, which is located to one side. The heater housing is made in two halves, which are joined along the centre line of the vehicle. Control flaps, heat exchanger and fan are installed in the halves of the housing. The heater is installed from outside in a chamber which is separate from the engine compartment.

The blades of the single-entry radial fan are curved forwards. The drive motor is completely sealed from the outside, and is mounted in the left half of the heater housing. The motor is cooled by air diverted from the fan volute. The fan has three speed settings controlled via resistances. When the controls are set to 'ventilation', one series resistance is short-circuited to raise the fan speed by an amount corresponding roughly to one speed setting. The fan volute widens both radially and axially.

Air can be directed either through the heat exchanger or through the bypass by means of two interlinked temperature mixing flaps. This makes it possible to set any desired air outlet temperature. The cold and warm air is not mixed completely at the point where the two flows merge. The upper part of the air duct is cooler than the lower part when the air is mixed. This feature is used to give the air emerging from the wide-section ventilation outlets a lower temperature than the air for the footwells. The air channelled to the defrosters is also cooler than the air at footwell level. This arrangement meets the requirement for temperature stratification as described in section 10.2.1, i.e. air at head level is cooler than the air supplied to the footwells. Since the system is air-flow controlled, temperature remains constant regardless of road speed.

Air distribution in the Audi 100 II is adjusted by a single lever among the heater controls. The two distribution flaps, which move in opposite directions, are therefore similarly interconnected. In the 'defrost' setting, with the distribution lever at the extreme right, all the air is directed through the defroster outlets in the facia. This setting gives optimum windshield demisting and de-icing. With the distribution lever in the other extreme position, 'ventilation', the air flow (increased by shorting out one of the series resistances) emerges from the many large outlets of the full-width ventilation. At intermediate settings the air is distributed between the various outlets. The air distribution giving best results under normal conditions is identified by a detent on the heater controls.

Some of the specifications of this heater system are:

Heat output with −20°C standard heat exchanger, approx.	8.9 kW
Heat output with −30°C cold-climate heat exchanger, approx.	10.4 kW
Area of heat exchanger 280 × 152 mm^2	426 cm^2
Depth of heat exchanger	42 mm
Maximum air flow on ventilation setting with vehicle stationary, windows etc. closed	11.6 kg/h

10.6 Summary

Physical well-being is not a matter of course. It is dependent on certain factors that influence the climate. The requirements for climate control in vehicles are as follows.

- When the interior is heated, temperature must be easily adjustable over a wide range, and must remain constant regardless of road speed.
- The warm air stream must not be aimed directly at the occupants.
- The air at head level should be about 7°C cooler than the air in the footwells.
- Relative air humidity should be between 30 and 70 per cent.
- For ventilation and air conditioning, it should be possible to aim cool air directly at the passengers. The direction and quantity of air flow should be adjustable. Air delivery should be over a wide area, and air speed should not be excessive. The flow rate should be kept low at the face, neck and wrists.

It has been shown that the scope for influencing climate factors by heating and ventilation for enhanced comfort is limited: in winter because of the relatively dry air, and in summer because it is not possible to reduce humidity levels. These can however be reduced with air conditioning.

The principal components of a heating and ventilation system have been discussed. In addition, the level of sealing or the amount of leakage from a car's body is of special importance—together with the air flow around the car—for the flow of air through the car, whether moving or stationary. The arrangement of air extraction outlets and the type of fan chosen both influence the air flow characteristics.

The characteristic curves of heat transferred by a heat exchanger explain the temperature variations of the heated air occurring with a water-flow controlled heater at small water flow rates. Temperature fluctuations when road speed is varied are much higher with water-flow controlled systems than with air-flow controlled systems, since in the latter case the heat exchanger operates constantly with almost saturation water flow, so an increase in water flow means only a small increase in heater output.

The actual heater configuration used in the Audi 100 II is described by way of an example.

10.7 Notation

A_e	equivalent leakage cross-section
$\dot{Q}_{100}$	heat flow, Fig. 10.10
$\dot{V}_{FL}$	coolant flow, Fig. 10.10
I	current, Fig. 10.12
U	voltage, Fig. 10.12
a	relative heater control valve travel, Fig. 10.13
h	enthalpy, Figs 10.4, 10.5, 10.6
$\dot{m}$, $\dot{m}_L$	air mass flow
n	revolutions of the fan, Fig. 10.12
p_i	pressure inside the passenger compartment
t_i	averaged temperature inside the passenger compartment
t_a	temperature of ambient (external) air
x	water content of air, Figs 10.4, 10.5, 10.6
ρ_L	density of air