Related Commercial Resources

CHAPTER 9

AUTOMOBILES AND MASS TRANSIT

AUTOMOBILES

THERMAL systems in automobiles (HVAC, engine cooling, transmission, power steering) have significant energy requirements that can adversely affect vehicle performance. New and innovative approaches are required to provide the customer the desired comfort in an energy-efficient way. In recent years, efficiency of the thermal systems has increased significantly compared to systems used in the early to mid-1990s. Providing thermal comfort in an energy-efficient way has challenged the automotive industry to search for innovative approaches to thermal management. Hence, managing flows of heat, refrigerant, coolant, oil, and air is extremely important because it directly affects system performance under the full range of operating conditions. This creates significant engineering challenges in cabin and under-hood thermal management. Optimization of the components and the system is required to fully understand the components' effects on the system. Thus, modeling the components and the system is essential for performance predictions. Simulation of thermal systems is becoming an essential tool in development phase of projects. Durability and reliability are also important factors in design of these systems.

Environmental control in modern automobiles usually consists of one (or two for large cars, trucks, and sport utility vehicles) in-cabin air-handling unit that performs the following functions: (1) heating, (2) defrosting, (3) ventilation, and (4) cooling and dehumidifying (air conditioning). This unit is accompanied by an under-hood vapor cycle compressor, condenser, and expansion device. The basic system can be divided into three subsystems: air handling, heating, and refrigeration (cooling). All passenger cars sold in the United States must meet defroster requirements of the U.S. Department of Transportation (DOT) Federal Motor Vehicle Safety *Standard* 103 (FMVSS), so ventilation systems and heaters are included in the basic vehicle design. The most common system today integrates the defroster, heater, and ventilation system. In the United States, the vast majority of vehicles sold today are equipped with air conditioning as original equipment.

DESIGN FACTORS

General considerations for design include cabin indoor air quality (IAQ) and thermal comfort, ambient temperatures and humidity, operational environment of components, airborne contaminants, vehicle and engine concessions, physical parameters, durability, electrical power consumption, cooling capacity, occupants, infiltration, insulation, solar effect, vehicle usage profile, noise, and vibration, as described in the following sections.

Thermal Comfort and Indoor Air Quality (IAQ)

ASHRAE *Standard* 55 provides information on the airflow velocities and relative humidity required to provide thermal comfort. Effective comfort cooling system design in cars must create air movement in the vehicle, to remove heat and occupants' body effluents and to control moisture build-up. Assuming an effective temperature of 71°F with no solar load at 75°F, 98% of people are comfortable with zero air velocity over their body. If the temperature increases to 81°F, the same number of people are comfortable with an air velocity of 500 fpm. If panel vent outlets can deliver sufficient air velocity to the occupants, comfort can be reached at a higher in-vehicle temperature than with low airflow (Figure 1).

Several modeling manikins for predicting human physiological behavior are described in Guan et al. (2003a, 2003b, 2003c), Jones (2002a, 2002b), and Rough et al. (2005).

During the increasingly common gridlock or stop-and-go conditions, **tailpipe emissions** can make outside air (OA) extremely polluted, and it is important to ensure that passengers' exposures to these gases do not exceed ACGIH (2007) short- or long-term exposure limits.

Tailpipe emissions include

- Nitrogen oxides (NO_x), which include both nitric oxide (NO) and nitrogen dioxide (NO_2), which always occur together (Pearson 2001)
- Carbon monoxide (CO), which forms in the combustion chamber when oxygen supply is insufficient
- Hydrocarbons (HCs)
- Volatile organic compounds (VOCs)

Diesel engines emit mainly NO_x and HC, and gasoline engines emit mainly CO and HC. Worldwide, road transportation accounts for approximately 50% of NO_x emissions, and gasoline-powered

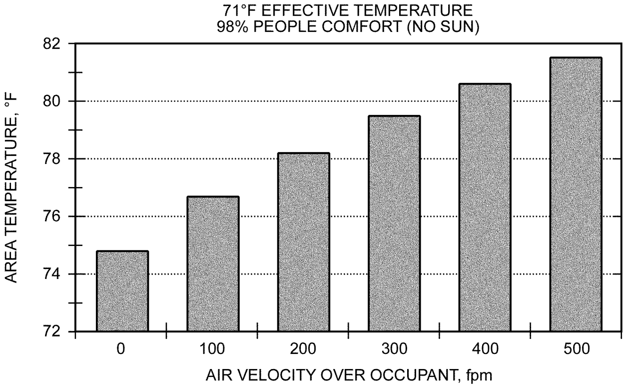


Fig. 1 Comfort as Function of Air Velocity
(Atkinson 2000)

The preparation of this chapter is assigned to TC 9.3, Transportation Air Conditioning.

vehicles alone account for 32% of HC emissions in the United States.

To limit passengers' exposure to tailpipe emissions, the blower unit's air intake door can be switched from outside air mode to recirculation mode during times of traffic congestion and likely poor OA quality (Mathur 2006).

Carbon dioxide (CO_2) from passengers' exhalations can also build up in the cabin, especially in low-body-leakage vehicles, so recirculation mode should not be used for extended periods. A recommended strategy is to limit recirculation to a relatively short period (e.g., 30 min), after which the system switches to OA. A CO_2 sensor can be installed to monitor levels in the cabin, and automatically switch to OA mode when set levels are exceeded.

Relative humidity also affects cabin IAQ. Too high a level affects occupant comfort and can lead to condensation and fogging on windows. A relative humidity sensor can detect excessive humidity and intervene.

See the section on Controls for more information on cabin IAQ.

Cooling Load Factors

Occupancy. Occupancy per unit volume is high in automotive applications. The air conditioner (and auxiliary evaporators and systems) must be matched to the intended vehicle occupancy.

Infiltration. Like buildings, automobiles are not completely sealed: wiring harnesses, fasteners, and many other items must penetrate the cabin. Infiltration varies with relative wind/vehicle velocity. Unlike buildings, automobiles are intended to create a relative wind speed, and engines may emit gases other than air. Body sealing and body relief vents (also known as the drafter) are part of air-conditioning design for automobiles. Occasionally, sealing beyond that required for dust, noise, and draft control is required.

By design, vehicles are allowed to have controlled body leakage that allows air movement in the vehicle to provide comfort to the passengers. This also helps control moisture build-up and the occupants' perceived comfort level. However, excessive body leakage results in loss of heating and cooling performance. Vehicle body leakage characteristics typically are significantly different in dynamic conditions in comparison to the static conditions. Air can leak from the vehicle's doors, windows, door handles, and trunk seals (uncontrolled exit points); drafters allow a controlled exit for air from the cabin, and should be self-closing to prevent inflow when the body pressure is negative with respect to the exterior pressure. According to SAE *Standard* J638, infiltration of untreated air into the passenger compartment through all controlled and uncontrolled exit points should not exceed 350 cfm at a cabin pressure of 1 in. of water (Atkinson 2000). However, each vehicle has different body leakage characteristics. Some vehicles have two drafters inside the trunk on either side, and some have only one.

Insulation. Because of cost and weight considerations, insulation is seldom added to reduce thermal load; insulation for sound control is generally considered adequate. Additional dashboard and floor thermal insulation helps reduce cooling load. Some new vehicles have insulated HVAC ducts to reduce heat gain during cooling and heat loss during heating mode. Typical interior maximum temperatures are 200°F above mufflers and catalytic converters, 120°F for other floor areas, 145°F for dash and toe board, and 110°F for sides and top.

Solar Effects. The following four solar effects add to the cooling load:

- **Vertical.** Maximum intensity occurs at or near noon. Solar heat gain through all glass surface area normal to the incident light is a substantial fraction of the cooling load.
- **Horizontal and reflected radiation.** Intensity is significantly less, but the glass area is large enough to merit consideration.
- **Surface heating.** Surface temperature is a function of the solar energy absorbed, the vehicle's interior and exterior colors, interior and ambient temperatures, and the automobile's velocity.
- **Vehicle colors and glazing.** The vehicle's interior and exterior colors, along with the window glazing surfaces (clear or tinted), strongly affect vehicle soak temperature. Breathing-level temperatures after a 1 h soak can be 40 to 60°F higher than ambient, with internal surfaces being 50 to 100°F above ambient (Atkinson 2000).

Ambient Temperatures and Humidity. Several ambient temperatures need to be considered. Heaters are evaluated for performance at temperatures from – 40 to 70°F. Air-conditioning systems are evaluated from 40 to 110°F, although ambient temperatures above 125°F are occasionally encountered. The load on the air-conditioning system is also a function of ambient humidity (at most test conditions this latent load is around 30% of the total). Typical design points follow the combinations of ambient temperature and humidities of higher probability, starting at around 90% rh at 90°F and with decreasing humidity as temperature increases.

Because the system is an integral part of the vehicle, the effects of vehicle-generated local heating must be considered. For interior components, the design high temperature is usually encountered during unoccupied times when the vehicle is soaked in the sun. Interior temperatures as high as 190°F are regularly recorded after soaks in the desert southwestern United States. Achieving a comfortable interior temperature after such a hot soak is usually one of the design conditions for most vehicle manufacturers.

Operational Environment of Components

Underhood components may be exposed to very severe environments. Typical maximum temperatures can reach 250°F. The drive to achieve more fuel-efficient automobiles has reduced available space under the vehicle hood to a minimum. This crowding exposes many components to temperatures approaching that of exhaust system components. Heat from the vehicle also adds to the cooling loads that the air-conditioning system must handle. During idle, heat convected off the hood can raise the temperature of the air entering the air inlet plenum by as much as 10 to 25°F (Mathur 2005a). A similar effect is found during idle when air from the engine compartment is reentrained into the air flowing through the condenser (Mathur 2005b). Air temperatures as high as 160°F have been encountered on parts of a vehicle's condenser during operation with a tail wind in ambient temperatures as low as 100°F. Typically, front air management is improved by using air guides and seals to prevent air bypassing either the condenser or radiator at idle. Significant improvements in vent outlet temperatures (a maximum of 7°F) and cabin temperatures (2 to 6°F) and a reduction in head pressures (30 to 77 psi) have been obtained. Recirculation of hot engine compartment air was reduced from 52.2°F over ambient (base case) to approximately 27°F over ambient. Further details are provided in the section on Vehicle Front-End Design.

Airborne Contaminants and Ventilation

Normal airborne contaminants may include bacteria, pollutants, vapors from vehicle fluids, and corrosive agents (Mathur 2006). Exposure to these must also be considered when selecting materials for seals and heat exchangers. Incorporating particulate and/or carbon filters to enhance interior air quality (IAQ) is becoming common. Air-handling systems in virtually all vehicles are capable of exceeding the ventilation recommendations for buildings and public transportation in ASHRAE *Standard* 62.1. However, the driver has complete control of the HVAC system in the vehicle, and can reduce cabin airflow to virtually zero when desired (e.g., before warm-up on cold days).

Power Consumption and Availability

Many aspects of vehicle performance have a significant effect on vehicular HVAC systems. Modern vehicles have a huge variety of electric-powered systems. The need to power these systems while maintaining fuel efficiency leads manufacturers to demand a high level of efficiency in electrical power usage. On some vehicles, electrical power use is monitored and reduced during times of minimal availability. The mass of the HVAC system is also closely controlled to maintain fuel efficiency and ride or handling characteristics. The power source for the compressor is the vehicle’s engine. At engagement, the need to accelerate the rotational mass as well as pump the refrigerant can double the engine torque. This sudden surge must not be perceptible to the driver, and is controlled through careful calibration of the engine controls. Automotive compressors must provide the required cooling while compressor speed varies with the vehicle condition rather than the load requirements. Vehicle engine speeds can vary from 500 to 8000 rpm.

Physical Parameters, Access, and Durability

The durability of vehicle systems is extremely important. Hours of operation are short compared to commercial systems (160,000 miles at 40 mph = 4000 h), but the shock, vibration, corrosion, and other extreme conditions the vehicle receives or produces must not cause a malfunction or failure. Automotive systems have some unique physical parameters, such as engine motion, proximity to components causing adverse environments, and durability requirements, that are different from stationary systems. Relative to the rest of the vehicle, the engine moves both fore and aft because of inertia, and in rotation because of torque; this action is referred to as **engine rock**. Fore and aft movement may be as much as 0.5 in.; rotational movements at the compressor may be more than as 0.75 in. from acceleration and 0.5 in. from deceleration when the length to center of rotation is considered. Additionally, the need for components to survive bumper impacts of up to 5 mph leads to additional clearance and strength requirements. Vehicle components may also be exposed to many different types of chemicals, such as road salt, oil, hydraulic fluid (brakes and power steering), and engine coolant.

The automobile is also increasingly incorporating electrical and electronic components and functionality. This requires manufacturers to both limit the emissions of electrical signals from components as well as ensure that all components will work when subjected to these same types of emissions. Manufacturers’ requirements for electromagnetic compatibility are increasingly stringent regarding the frequencies of radio and communication devices.

Wiring, refrigerant lines, hoses, vacuum lines, and so forth must be protected from exhaust manifold heat and sharp edges of sheet metal. Normal service items such as oil filler caps, power steering filler caps, and transmission dipsticks must be accessible. Air-conditioning components should not have to be removed to access other components.

Noise and Vibration

The temperature control system should not produce objectionable sounds. During maximum heating or cooling operation, a slightly higher noise level is acceptable. Thereafter, it should be possible to maintain comfort at a lower blower speed with an acceptable noise level. Compressor-induced vibrations, gas pulsations, blower motor vibration, and noise must be kept to a minimum. Suction and discharge mufflers are often used to reduce noise. Belt-induced noises, engine torsional vibration, and compressor mounting all require particular attention. Manufacturers have different requirements and test methods. Although it is almost impossible to predict vehicle sound level from component testing, a decrease in the sound and vibration energy at the source of noise will always decrease the noise level in vehicle (assuming there is not a shift in frequency), so most automobile manufacturers require continuous improvement in overall component sound level.

Vehicle Front-End Design

Front-end design affects performance of the climate control and engine cooling systems, especially at low speeds and at idle. The design should ensure that the air flowing into the front end through the bumper and/or grille does not bypass either the condenser or radiator from the sides, top, or bottom. Air will take the path of least resistance, and if not forced over the heat exchangers, it will usually bypass them. In a good design, the condenser and radiator are the same size, and should not have space between (Mathur 2005b). This eliminates the use of seals between the condenser and radiator. Typically, the front-end module has components in the following sequence: condenser, radiator, and fans (CRF); these systems are known as condenser-radiator-fan modules (CRFM). A good front-end design provides optimum performance for both air-conditioning and engine-cooling systems. Airflow over the front end couples these two systems; thus, performance of one system (e.g., air conditioning) influences the other system (engine cooling). This is most evident at idle.

In a typical design, sheet metal covers the entire area on the sides of the condenser. This prevents air from bypassing from either side of the condenser and radiator. To prevent recirculation of the hot engine compartment air at idle, the front bottom part of the front end is usually covered by sheet metal or plastic sheet. To limit recirculation on the top, a seal that sits on the cross frame when the hood is closed is usually added. This prevents recirculation of the hot engine compartment air to approximately the top and bottom thirds of the condenser. Without this, the condenser head pressure may increase greatly, further degrading system performance.

Enhanced R-134a systems, the next-generation AC system, require substantial changes to hardware and controls to achieve performance and energy requirement targets, although some of the strategies described here can be used to approach the targets.

AIR-HANDLING SUBSYSTEM

The in-cabin air-handling unit, commonly called an **air-conditioning module (ACM)**, provides air to the passenger cabin. It incorporates the following basic components: heater core, evaporator core, blower motor, air-distribution control, ram air control, body vents, and air temperature controls. In addition to the ACM, an air inlet plenum, distribution ducting, outlets, and body relief vents or drafters make up the complete air-handling subsystems. The evaporator core is a part of both the refrigeration and air-handling subsystems and forms the link between the two. The heater core is similarly the link with the heating subsystem.

The basic function of the air-handling system is as follows. The air intake valve allows air from either the exterior [taken directly from the air intake plenum or outside air (OA)] or the cabin to be recirculated to the fan. The fan then pumps air through the evaporator and into the temperature control door, which forces the air to either flow through or bypass the heater core to obtain the desired temperature. The air then moves to the distribution area of the module, where it is directed to one or more of the heater, ventilation, or defrost outlets. Air in the cabin then either is recirculated or exits out of the vehicle through body vents or drafter(s).

There are many variations on the basic ACM system. Common ones include regulating the air discharge temperature using coolant flow control and separating the ACM into two or more subcomponents to better fit the system in the vehicle.

Air Delivery Modes

There are three basic modes in most vehicles: heater, defroster, and air conditioning (or vent for vehicles without air conditioning). Typical mixed modes include bilevel, blend, and ambient.

Heater Mode. Heater mode is designed to provide comfort heating to vehicle occupants. Typical maximum heater airflow is 125 to 200 cfm for a mid-sized automobile. Heater air is generally distributed into the lower forward (foot) compartment, under the front seat, and up into the rear compartment. Air distribution near the floor also makes the vehicle more comfortable by providing slightly cooler air at breathing level. Because the supply air temperature is relatively high, direct impingement on the occupant is not desirable. Heater air exhausts through body leakage points.

Heater mode warms air in the vehicle above the dew points of the surrounding air and of the vehicle's glass. To prevent condensation from occupant respiration or from rain or snow tracked in, most vehicles sold in North America draw only OA when in heater mode and do not allow recirculation. However, some vehicle designs do allow recirculation, avoiding the higher cost of including the electric or vacuum actuation system necessary to prevent it.

Most vehicles also provide a small bleed of air (typically 15 to 25% of the total air flow) in heater (foot) mode to the windshield to isolate it from the car's interior. Properly designed, this prevents loss of visibility by window fogging under most conditions.

Defrost Mode. Defrost mode is provided to clear the windshield from frost and fog, both internally and externally. Typical maximum airflow for defrost systems is 150 to 200 cfm for a mid-sized automobile. Defrost mode requirements are given in the DOT's Federal Motor Vehicle Safety *Standard* (FMVSS) 103, which defines areas on the windshield for driver vision and a time frame in which they must be able to be cleared under extreme vehicle operating conditions. Most vehicles are also equipped with side window demisters that direct a small amount of heated air and/or air with lowered dew point to the front side windows. Rear windows are typically defrosted by heating wires embedded in the glass.

As in heater mode, to prevent windshield fogging, most vehicles built in North America prevent air from being recirculated in defrost mode. In addition, many vehicles automatically operate the air-conditioning system in defrost if the ambient temperature is above a threshold (usually around 40°F). This provides an extra assist and safety factor by lowering the dew point of the air exiting the ACM to below ambient temperature.

Air-Conditioning (or Panel) Mode. The air-conditioning mode is provided for occupant comfort cooling and to ventilate the vehicle. Typical airflow for panel mode is 200 to 300 cfm in a mid-sized car. Because of the lower temperature differentials in this mode, airflow is provided in such a way that direct impingement on the occupants can be achieved if desired. A minimum air velocity of 2000 fpm at the outlet is desired, to provide adequate comfort to occupants sitting in the front and rear of the cabin (Atkinson 2000). As discussed in the Design Factors section, the higher heat fluxes and higher initial temperature at vehicle start-up frequently require that the system be able to **spot cool**, providing the cooling airflow directly on the occupants, before lowering the overall cabin temperature. For these reasons, directability of the supply outlet on the occupants is very important. The air-conditioning system is designed to have sufficient capacity to bring the interior temperature down rapidly; panel outlets must also be positionable, to move the airflow off the occupants after a few minutes of operation.

Bilevel Mode. The most common mixed mode, bilevel mode is designed for moderate-temperature operation with high solar loading. The system provides air to both the lower outlets and the panel outlets. Typically, air from the panel outlets is 5 to 25°F cooler than the air from the lower outlets. This is to provide cooling to areas of the interior that have direct solar loading and to provide warm air to those that do not.

Blend Mode. The next most common mixed mode is blend mode, designed to provide a step between heater and defroster for times when extra heat is needed to keep the windshield clear but full defrost is not desired. A typical situation where blend mode is used is in city traffic during snowfall. The extra airflow to the windshield helps maintain a clear field of vision and still maintains adequate flow to lower outlets to keep occupants warm.

Outside Mode. This mode is also designed for mild ambients. It is intended to provide a relatively high total airflow through the cabin but without the high local air velocities of the other modes. Typically, vehicles with outside mode are also equipped with additional panel outlets not directed toward the occupants. The most common configuration provides air toward the ceiling from outlets in the middle of the dashboard.

Controls

The HVAC control head (i.e., the controls for the ACM and the refrigeration system) is located within easy reach of the driver and occupants. These controls must be easy to use and not distract the driver from the road. There are many variations of HVAC controls in automobiles, from the cable-controlled manual system to fully automatic systems that control the cockpit environment. The two main classifications are manual and automatic.

The **manual control** is typically the base system that provides control for mode, temperature valve position, air source, and air flow rate (blower speed). In addition to air-handling controls, the control head usually also has a button to engage the compressor (i.e., to turn on the AC system). Additional functions, such as rear defrost and seat heating controls, are frequently added to the control head. Although manual control provides a temperature mix door control, this is not a temperature control; it only controls the opening of the temperature valve and fixes the amount of air that bypasses the heater core. Therefore, if there is significant variation in ambient temperature or vehicle coolant temperature, the manual system will need to be adjusted. Manual systems typically have four or five blower speeds.

Automatic control uses a control unit and vehicle sensors to establish a comfortable thermodynamic environment for vehicle occupants. Sensors measure air inlet temperature, vehicle cabin temperature, and ACM discharge air temperature. The automatic control will then vary the mix door position, airflow rate, ACM mode, and air-conditioning compressor engagement. Some advanced systems measure cabin humidity for comfort control. Automatic systems usually have from 8 to 20 blower speeds.

Air quality control is also becoming available in many vehicles. Most of these systems assume that a vehicle will quickly pass through areas where the contamination source is prevalent. A sensor measures a **surrogate gas** (a gas that is not necessarily toxic but accompanies toxic gases that are more difficult to measure). When the surrogate gas is detected, the vehicle's air inlet door is positioned for recirculation to separate the occupants from the contamination source.

Air-Handling Subsystem Components

Air Inlet Plenum. The air inlet plenum (also called a **cowl**) is usually an integral part of the vehicle structure. There are two primary design considerations and several secondary design considerations for the air inlet plenum:

Primary

- Air that flows into the plenum should not be influenced by uncontrolled emissions from the vehicle systems; in other words, the plenum should be a source of clean air.
- The plenum should be located so that the aerodynamic effects of air movement over the vehicle increase pressure in the plenum, so when the vehicle operates with external air selected, air flows through the air-handling unit into the vehicle. This allows fresh air to flow through the vehicle and helps reduce the amount of external air that infiltrates into the vehicle from uncontrolled sources.

Secondary

- The pressure drop of the plenum should also be considered. Higher airflow pressure requires that more power be available to the ACM blower and fan to provide adequate airflow.

- Airflow at the entrance to the ACM's blower should be uniform. In many vehicle applications, a significant loss in efficiency is caused by unbalanced airflow into the fan.
- The air inlet plenum must also serve several other functions, such as water separation, protection from snow ingestion, and gross filtration (usually through a screen).
- The air inlet plenum must also be located such that when the vehicle is covered by snow, the plenum will still be able to furnish sufficient air to clear the windshield and provide fresh air to the occupants.

The air inlet plenum is usually located at the base of the windshield. If properly sealed from the underhood areas of the vehicle, this provides a relatively high-pressure and clean source of air. Major plenum design considerations include the following (Mathur 2005a).

Separation of Water Droplets from Airstream. It is important that openings in the plenum cover be sized carefully. Openings that are too small result in a higher pressure, which reduces airflow and increases noise. Reduced airflow increases window fogging and significantly decreases occupants' perceived comfort. Surface tension can also cause rainwater to plug small openings and get sucked into the plenum when the blower is turned on in OA mode. On the other hand, very large openings can allow snow or sleet inside, where it can accumulate and ultimately block the path of airflow. Plenum cover opening sizes should be optimized to address both these issues.

Water droplets follow the air trajectory inside the plenum. Removing the droplets requires changing the airflow direction: because their momentum is greater, the droplets do not change direction but instead hit the sheet metal wall and then drain to the bottom of the plenum channel. Otherwise, filters may become saturated with water. Adding baffles inside the plenum channel can change airflow direction, but also increases air pressure drop, which affects both airflow rate and noise levels. Angling baffles in the flow direction helps alleviate this pressure drop increase.

Expanding the plenum's cross-sectional area is another way of removing water droplets from the air stream, but is not always possible because of space limitations. This is a good approach, though, around the wiper motor and linkages, which are housed inside the plenum channel and significantly reduce airflow area.

Snow Separation. As discussed previously, plenum cover opening size is crucial in keeping precipitation out of the plenum. Even with an optimum cover design, though, accumulated snow must be removed before the blower unit is turned on in OA mode. Otherwise, dry, powderlike snow could enter the plenum and end up on the filter, saturating it and causing fogging issues.

Hard snow over the plenum cover is difficult to remove and significantly reduces airflow when the blower is turned on. As air flows over the openings, some of the ice is directly evaporated into the air stream by sublimation, increasing window fogging. To address this situation, some plenum cover openings in newer cars are under the hood, allowing some airflow into the cabin in this situation. Note, however, that this approach could be lethal in old cars that leak exhaust gases from faulty gaskets under the hood.

Distribution Ducting. Air from the air-handling unit is distributed to various areas of the vehicle through ducting. Typically, the main trunk duct exits the ACM near the middle of the dashboard. Ducting carries the air from this central location to the extremes of the instrument panel, the floor, and even the rear seat (if so equipped). The design goal for the distribution ducting is to distribute air throughout the vehicle with as little pressure drop as possible, to provide sufficient airflow to the various outlets for occupant comfort. This goal is frequently compromised by the tight packaging constraints in modern vehicles. Ducts should be designed with no sharp edges inside the airflow stream, which could increase airflow rush noise.

Outlets. There are typically defrost, heater, side window, and panel air outlets in a vehicle. The defrost air outlet is located on top the instrument panel to distribute air to clear the windshield of frost and fog as quickly and efficiently as possible. Heater outlets are located on the bottom of the instrument panel to spread warm air over the floor of the vehicle. Panel outlets are designed to provide cool air to the occupants. The importance of panel outlets should not be underestimated. The ability to achieve direct air impingement on occupants with little diffusion is very important to comfort after a vehicle has been inoperative during extremely hot summer conditions. Likewise, it is important to be able to direct the cool air away from occupants after the interior begins to cool down. The air pressure drop in the vent outlet changes as the direction of the vane or blade is changed, and can result in reduced airflow. This is necessary to direct the airflow over the desired area of the passenger. The ability to direct the jet air and reach the occupants under all conditions can result in satisfied consumers; the lack of this ability has resulted in dissatisfied consumers even in vehicles with exceptional airflow and capacity.

Body Relief Vents or Drafters. Body relief vents or drafters are designed to ensure airflow through the vehicle from front to rear. The drafters are located inside the trunk, under the carpet, on the sides near the wheel wells. Air flows from the cabin into the trunk through parcel shelf openings (holes that facilitate airflow from cabin to trunk), and then between the sheet metal and carpet to the drafters. Typically, they are effectively low-pressure check valves, designed to allow airflow out of the vehicle when cabin pressure is above the local exterior pressure and to prevent air infiltration when the local exterior pressure is above that of the interior (i.e., when the vehicle is using recirculated air as the air source). Relief vents should be located where they will cause the airflow inside the body to cover all occupant locations inside the vehicle.

A small number of openings in the vehicle body are required for wires, cables, and various attachment features; therefore, the body relief vent does not typically need to be sized large enough to exhaust the total airflow through the vehicle.

Heater Core. The heat transfer surface in an automotive heater is generally either copper/brass cellular, aluminum tube and fin, or aluminum-brazed tube and center. Each of these designs is in production in straight-through, U-flow, or W-flow configurations. The basics of each of the designs are outlined as follows:

- The **copper/brass cellular** design is not used frequently in new vehicles. It uses brass tube assemblies (0.006 to 0.016 in. wall thickness) as the water course, and convoluted copper fins (0.003 to 0.008 in. thick) held together with a lead/tin solder. The tanks and connecting pipes are usually brass (0.026 to 0.034 in. wall thickness) and again are attached to the core by a lead/tin solder.
- The **aluminum tube-and-fin** design generally uses round copper or aluminum tubes, mechanically joined to aluminum fins. U tubes can take the place of a conventional return tank. The inlet/outlet tank and connecting pipes are generally plastic and attached to the core with a rubber gasket.
- The **aluminum-brazed tube-and-center** design uses flat aluminum tubes and convoluted fins or centers as the heat transfer surface. Tanks are either plastic and clinched onto the core or aluminum and brazed to the core. Connecting pipes are constructed of various materials and attached to the tanks a number of ways, including brazing, clinching with an O ring, fastening with a gasket, and so forth. Almost all original equipment manufacturers (OEMs) currently use brazed-aluminum heater cores (Jokar et al. 2004).

Air-side design characteristics include pressure drop and heat transfer. The pressure drop of the heater core is a function of the fin/louver geometry, fin density, and tube density. Capacity is adjusted by varying the face area of the core to increase or decrease the heat transfer surface area, adding coolant-side turbulators, or varying air-side surface geometry for turbulence.

Evaporator. Automotive evaporator materials and construction include (1) copper or aluminum tube and fin; (2) brazed-aluminum plate and fin, also known as a laminate evaporator; and (3) brazed serpentine tube and fin. This section addresses the air-side design of the evaporator. Air-side design parameters include air pressure drop, capacity, and condensate control.

A laminate evaporator consists of a number of stamped plates and louvered fins. The plates have clad material on both sides. The plates and fins are stacked and then either vacuum-brazed or controlled-atmospheric brazed (CAB). The advantage of using CAB is that it is a continuous process, whereas vacuum brazing is a batch process. When brazed, the plate forms internal flow passages for refrigerant. The plates have diagonal ribs (or multiple dimples) to augment heat transfer and provide strength, and central partitioning ribs that facilitate reversal of refrigerant flow. These evaporators may have tanks on both ends or on one end only. For the same airflow area, a single-tank evaporator has better performance than a double-tank evaporator, because the available heat transfer area is greater (i.e., the ratio of total heat exchange area to total volume of the core is higher for evaporators with single tanks). Laminate evaporators typically have four to six refrigerant passes. Two-phase refrigerant enters the evaporator through the inlet pipe, and vapor exits the evaporator through the outlet pipe. Two-phase refrigerant enters the evaporator through the tank and moves downward in multiflow channels (or plates) in pass 1 and then flows upward in pass 2. The refrigerant reaches the tank section at the top and then flows downward in pass 3, flows upward in pass 4, and exits the evaporator as vapor (Mathur 2000a, 2001b, 2002, 2003a).

Typically, an ACM is designed to provide the airflow required to provide cooling for the vehicle. The combination of airflow, maximum allowable current draw for the blower motor, size constraints on the ACM, and ductwork act together to establish a required evaporator air-side pressure-drop characteristic. The air-side pressure drop of the core is typically a function of fin spacing, louver design, core depth, and face area. This characteristic varies with accumulation of condensate on the core, so adequate leeway must be allowed to achieve target airflow in humid conditions.

Conditions affecting evaporator capacity are different from those in residential and commercial installations in that the average operating time, from a hot-soaked condition, is less than 20 min. Inlet air temperature at the start of operation can be as high as 160°F, but decreases as the vehicle duct system is ventilated. Capacity requirements under multiple conditions must be considered when sizing an automotive evaporator, including steady-state operation at high or low speeds, and a point in a cooldown after an initial vehicle hot soak. Some of these requirements may also be set in recirculating conditions where the temperature and humidity of inlet air decrease as the car interior temperature decreases.

The evaporator load also has a slightly higher sensible heat portion than indicated by ambient temperature. The heat gain from the vehicle and the temperature rise across the blower motor must be considered when sizing the evaporator.

During longer periods of operation, the system is expected to cool the entire vehicle interior rather than just produce a flow of cool air. During sustained operation, vehicle occupants want less air noise and velocity, so the air quantity must be reduced; however, sufficient capacity must be preserved to maintain satisfactory interior temperatures.

Condensate management is very important within a motor vehicle. In the process of cooling and dehumidifying the air, the evaporator extracts moisture from the air. It is imperative that condensate be prevented from entering the vehicle interior as a liquid, because this will damage the vehicle. This moisture should be carried out of the vehicle and not allowed to collect inside the ACM (Mathur 2000b). A distinct odor can be identified in many cars that have plugged condensate drain holes. This odor is given off by common organisms, present almost everywhere, that grow in warm, moist environments.

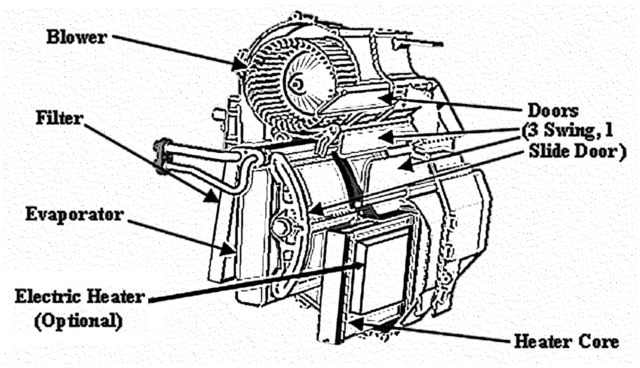


Fig. 2 Integrated HVAC Unit

Condensate management includes the following design objectives (Mathur 1999a):

- Ensure that moisture coming off the evaporator is in large enough droplets that it is not carried by the airstream (a combination of low velocity at the exit of the core and adequate ability of the core to allow surface tension to gather the water)
- Allow sufficient fin spacing for adequate condensate drainage
- Allow a large enough sump so that all water coming off the core can be collected for a short period of time when vehicle-maneuvering forces push water away from the drain
- Provide sufficient slope to the drain area so that water flows to the drain rather than collecting in the case
- Have a sufficient cross section in the drain so that water does not back up into the module, taking into account the fact that ACM interior pressure is usually 1 to 2 in. of water above the exterior pressure

Vehicle attitude (slope of the road and inclines), acceleration, and deceleration should also be considered because these factors have a significant effect on the drain system design. Drains can become plugged not only by contaminants but also by road splash.

Location of HVAC Unit. The HVAC unit consists of the blower intake unit, cooling unit, and a heater unit. The system also has several ducts that feed air to different circuits. These units are mounted inside the **cockpit module (CPM)**. U.S.-made vehicles use **modular design**, in which the blower, evaporator, and heater are individual units. **Integrated units** (Figure 2) that combine all three functions into one component have been developed, but their design is complex.

Blower Motor and Fans. Airflow in an automobile must provide sufficient cooling air to passengers in both the front and rear seats. Designs for the blower motor and fan, which must fit in a relatively small space, are frequently a compromise between packaging, mass, airflow, and efficiency. Virtually all fans used in automotive ACMs are centrifugal, with fan diameters from 5.5 to 8 in. Typical motor current draws vary from 14 to 25 A, depending on factors affecting optimization of the particular application. Both forward- and backward-inclined fan blades have been used.

Automotive systems are achieving a significantly improved level of comfort. Much of this is due to reductions in the noise, vibration, and harshness (NVH) characteristics of the interior. This continued effort has required continuous improvement in the NVH characteristics of blower motor and fan assemblies. During integration of the blower motor and fan into the module, careful attention must be paid to any type of vibrational excitation the fan may impart to the ACM and other underdash components.

Electronic Blower Speed Control. Historically, the blower motor speed control was simply a selector switch that selected either from direct battery voltage at the blower motor or from one of two or more resistors in series with the blower motor to reduce voltage. In general, the lowest airflow selectable is usually driven by the need to provide adequate air pressure to cool the blower motor. Modern blower motor speed controls incorporate essentially infinite speed control using devices such as **pulse-width modulating (PWM)** controllers. The newer devices are usually found on upscale vehicles using automatic climate control systems, which reduce energy consumption and increase fuel efficiency. When incorporating devices such as PWMs into a vehicle system, careful attention needs to be paid to radio frequency interference because of the necessary proximity of all the electronics in a vehicle.

Valves. The typical ACM has valves for the air inlet source, temperature control (heater air bypass), and mode control. Some vehicles also have a ram air door, used to reduce ram effect at high speeds and provide consistent airflow. Door/valve designs are integral to the ACM design. Door types include flag style, rotary, guillotine, slider, and film valves. The optimal door type is almost always a function of the space in which a module must fit.

Actuators. Actuators on ACMs are usually cable, electric, and/or vacuum. **Cable-based actuation** is usually the least expensive and most frequently found in entry-level vehicles. The valving system must be designed to retain a position with minimal restraining torque, have smooth operation with essentially constant torque level, and have minimal torque required to move the valve(s). There must be a suitable cable path from the HVAC controls to the module. Cable actuation does not allow electronic control of the air-conditioning system or an interlock to ensure outside air is selected in defrost mode.

The norm for U.S. automobiles 20 years ago, **vacuum actuation**, has been replaced by electronic actuators. Vacuum actuators can provide only three position controls per actuator and require a cross-sectional area for the diaphragm proportional to the load on the door. The vacuum source is the vehicle's engine intake air manifold. Although this provides a powerful control at engine idle, a great deal of variation exists in the working pressure differential, and must be taken into account in system design.

Electric actuators can control the ACM electronically and are available in variety of shapes. The possibility of linear positions allows for multiple modes, with one actuator on several doors, using a cam system. They also isolate the operator from torque variations, allowing the ACM to be optimized for other performance criteria.

Air Inlet. The air inlet interfaces the ACM with the vehicle body. If not accomplished upstream, it is necessary for the air inlet to separate out water that may have been ingested from rain, carwashes, etc. It also provides the selection of either outside air or air recirculated from the passenger compartment. On upscale performance vehicles, the ram air door is also located here. A primary design criterion for the air inlet is to provide proper flow patterns at the inlet of the blower motor. In many applications this is compromised to fit the ACM into the vehicle. The result is either turbulence or misdistribution of air into the fan, causing noise and lower efficiency.

Mode Control. Air distribution is usually done at the ACM by one or more valves directing air to the desired vehicle outlets. This system may provide several discrete modes or a continuous variation from one mode to the next. ACM valving must be designed to work with the distribution ductwork and provide the desired air distribution to the occupants.

Air Distribution. Air distribution must be done in a way that minimizes pressure loss, thermal lag, and heat gain. Ductwork is usually designed around the other underdash components, and frequently must follow a difficult path. The air for all outlets starts at one basic plenum pressure, and variations in pressure drop versus flow rate from side to side in the vehicle must be minimized to provide even airflow to both driver and passengers. Because of the instrument cluster in front of the driver and devices such as airbags, ductwork is almost never laterally symmetrical. Computational fluid dynamics is used to ensure proper air distribution design.

Air Filter. Air filters are increasingly common, typically located in either the air inlet plenum or the ACM. Filters may be particulate, charcoal, or both; they require regular service to prevent clogging and ensure proper system function. Removal of contaminants (e.g., pollen) may also be aided by condensate on evaporator surfaces. The concentration of the volatile organic compounds (VOCs) from the vehicle's interior (plastic parts, carpet, adhesive, etc.) along with tailpipe emissions (NO_x, CO, hydrocarbons) from automobiles, buses, and trucks can be reduced by using carbon filters. These filters should be replaced regularly, based on driving conditions, because a dirty filter can be the largest source for polluting cabin air.

HEATING SUBSYSTEM

The primary heat source is the vehicle's engine. Coolant from the engine cooling system circulates through the heater core. Modern efficiency and emissions improvements have led to many types of supplemental heating produced today, including fuel-fired heaters, refrigerant heat pumps, electrical heaters, and heat storage systems.

The heater core must be designed to work within the design of the engine cooling system. Engine coolant pressure at the heater core inlet ranges up to 40 psig in cars and 55 psig on trucks.

Modern antifreeze coolant solutions have specific heats from 0.65 to 1.0 Btu/lb·°F and boiling points from 250 to 272°F (depending on concentration) when a 15 psi radiator pressure cap is used.

Controls

Engine coolant temperature is controlled by a thermostatically operated valve that remains closed until coolant temperature reaches 160 to 205°F. Coolant flow is a function of pressure differential and system restriction, but typically ranges from 0.6 gpm at idle to 10 gpm at higher engine speed. Coolant temperature below 160°F is not desirable, because it cannot meet occupants' comfort requirements. The mechanical pump should be able to deliver sufficient coolant flow, even at idle.

Components

The minimal components of the heating subsystem are the coolant flow circuit (water pump) and temperature control, both provided by the vehicle's engine; the heater core (part of the ACM); and coolant hoses.

REFRIGERATION SUBSYSTEM

Cooling is almost universally provided by a vapor cycle system. The thermodynamics of a vapor cycle system are described in Chapter 1 of the 2005 *ASHRAE Handbook—Fundamentals*. The automotive system is unique in several ways.

Refrigeration capacity must be adequate to bring the vehicle interior to a comfortable temperature and humidity quickly and then maintain it during all operating conditions and environments. A design may be established by mathematical modeling or empirical evaluation of known and predicted factors. A design tradeoff in capacity is sought relative to criteria for vehicle weight, component size, and fuel economy. Automotive system components must meet internal and external corrosion, pressure cycle, burst, and vibration requirements.

Refrigerant-based system equipment is designed to meet the recommendations of SAE *Standard* J639, which includes several requirements for refrigerant systems. To be compliant, a system must have

- A high-pressure relief device

- Burst strength (of components subjected to high-side refrigerant pressure) at least 2.5 times the venting pressure of the relief device
- Electrical cutout of the clutch coil before pressure relief to prevent unnecessary refrigerant discharge
- Low-pressure-side components with burst strengths in excess of 300 psi

The relief device should be located as close as possible to the discharge gas side of the compressor, preferably in the compressor itself.

Controls

Refrigerant Flow Control. Cycling-clutch designs are the most common mechanisms for controlling refrigerant flow. Schematics for the two most common versions of this design are shown in Figures 3 and 4. The clutch is cycled by either a thermostat that senses evaporator temperature or a pressure switch that senses evaporator pressure. This thermostat or pressure switch serves two functions: it prevents evaporator icing, and it maintains a minimum refrigerant density at the inlet of the compressor, preventing overheating. Discharge air temperature is then increased, if necessary, by passing some (or all) of the evaporator outlet air through the heater core.

The clutch-cycling switch disengages at about 25 psig and engages at about 45 psig. Thus, the evaporator defrosts on each off-cycle. The flooded evaporator has enough thermal inertia to prevent rapid clutch cycling. It is desirable to limit clutch cycling to a maximum of six cycles per minute because a large amount of heat is generated by the clutch at engagement. The pressure switch can be used with a thermostatic expansion valve in a dry evaporator if the pressure switch is damped to prevent rapid cycling of the clutch.

Cycling the clutch sometimes causes noticeable surges as the engine is loaded and unloaded by the compressor. This is more evident in cars with smaller engines. This system cools more quickly and at lower cost than a continuously running system.

For vehicles where clutch cycling is unwanted because of engine surge, or for high-end vehicles where no perceptible temperature swing is allowable, variable-displacement compressors are available, controlled either electronically or pneumatically.

In the **pneumatically controlled compressor**, a sensor (usually located in the compressor body) varies the compressor displacement so that a constant pressure is maintained at the compressor inlet. This provides a nearly uniform evaporator temperature under varied loading conditions. This type of system causes no perceptible engine surge with air-conditioning system operation.

The **electronically controlled variable-displacement compressor** opens up many possibilities for systems optimization. This type of compressor allows reduced reheat control, and evaporator temperature is maintained at such a level that comfort is achieved with less fuel consumption. A wide range of control schemes using electronically controlled variable-displacement compressors are being developed.

Other Controls. A cycling switch may be included to start an electric fan when insufficient ram air flows over the condenser. Also, output from a pressure switch or transducer may be used to put the ACM into recirculation mode, which reduces head pressure by reducing the load on the evaporator. Other possibilities include a charge loss/low-ambient switch, transducer evaporator pressure control, and thermistor control.

Components

Compressor. Piston compressors dominate the automotive market, although scroll and rotary vane types are also significant. For detailed information on compressor design, see Chapter 34 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Figure 5 illustrates basic automotive compressor types. The typical automotive compressor has the following characteristics:

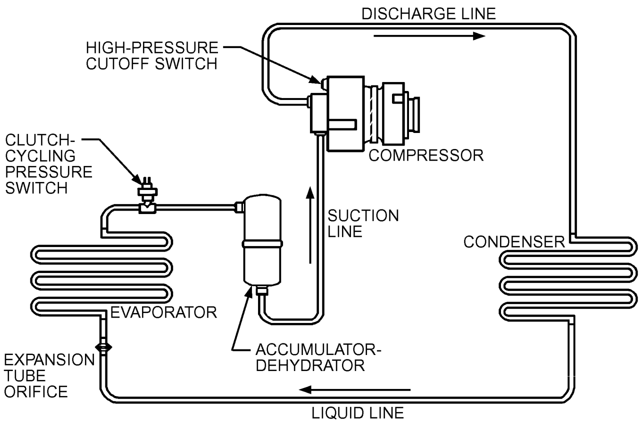


Fig. 3 Clutch-Cycling System with Orifice Tube Expansion Device

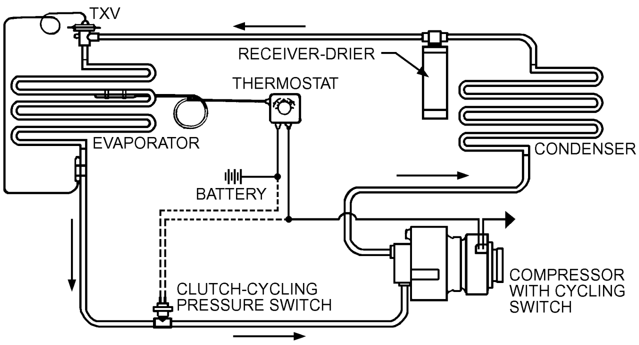


Fig. 4 Clutch-Cycling System with Thermostatic Expansion Valve (TXV)

- **Displacement.** Fixed-displacement compressors have displacements of 6.1 to 12.6 in^3/rev. Variable-displacement piston compressors typically have a minimum displacement of about 6% of their maximum displacement. A typical variable-capacity scroll compressor has a maximum displacement of 7.3 in^3/rev and a minimum displacement of 10% of the maximum.
- **Physical size.** Fuel economy, lower hood lines, and more engine accessories all decrease compressor installation space. These features, along with the fact that smaller engines have less accessory power available, promote the use of smaller compressors.
- **Speed range.** Most compressors are belt-driven directly from the engine; they must withstand speeds of over 8000 rpm and remain smooth and quiet down to 500 rpm. The drive ratio from the vehicle engine to the compressor typically varies from 1:1 to 2:1. In the absence of a variable drive ratio, the maximum compressor speed may need to be higher to achieve sufficient pumping capacity at idle.
- **Torque requirements.** Because torque pulsations cause or aggravate vibration problems, it is best to minimize them. Minimizing peak torque benefits the compressor drive and mount systems. Multicylinder reciprocating and rotary compressors aid in reducing vibration. An economical single-cylinder compressor reduces cost; however, any design must reduce peak torques and belt loads, which are normally at a maximum in a single-cylinder design.
- **Compressor drives.** A magnetic clutch, energized by power from the vehicle engine electrical system, drives the compressor. The clutch is always disengaged when air conditioning is not required. The clutch can also be used to control evaporator temperature (see the section on Controls).

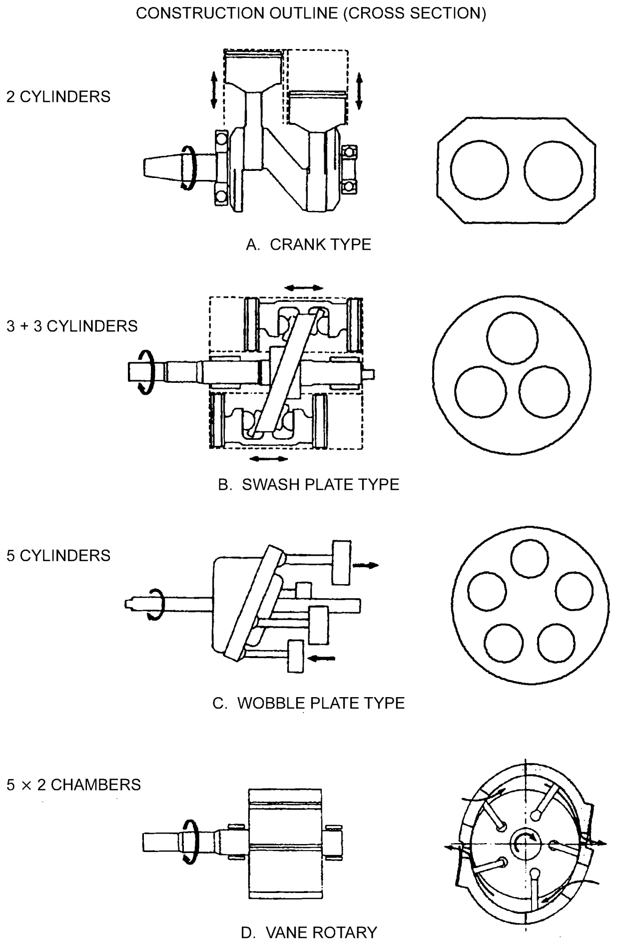


Fig. 5 Basic Compressor Designs for Automotive Application

- **Variable-displacement compressors.** Both axial and wobble plate variable-displacement compressors are available for automobile air conditioning. The angle of the plate changes in response to the suction and discharge pressure to achieve a constant suction pressure just above freezing, regardless of load. A bellows valve or electronic sensor-controlled valve routes internal gas flow to control the angle of the plate. A variable-displacement compressor reduces compressor power consumption, improving fuel efficiency. These compressors improve dehumidification and comfort, have low noise and vibration, and have high reliability and efficiencies.
- **Noise, vibration, and harshness.** With decreasing mass and increasing environmental quality in automobiles, compressor design is increasingly driven by NVH concerns. Vibrational input to the structure, suction and discharge line gas pulsations, and airborne noise must all be minimized. NVH minimization is now the main impetus behind most continuous improvement efforts in the automotive compressor industry.
- **Mounting.** Compressor mounts are an important part of a successful integration of a compressor into a vehicle system. Proper mounting of the compressor minimizes structural resonances and improves the NVH characteristics of any compressor.

Compressor Oil Return. It is important that there are no areas where the lubrication oil can accumulate (Mathur 2004a). At part-load conditions, refrigerant velocities should be high enough to ensure oil return to the compressor. The presence of oil in the system affects heat exchanger performance (Mackenzie et. al. 2004). Some new compressors have a built-in oil separator.

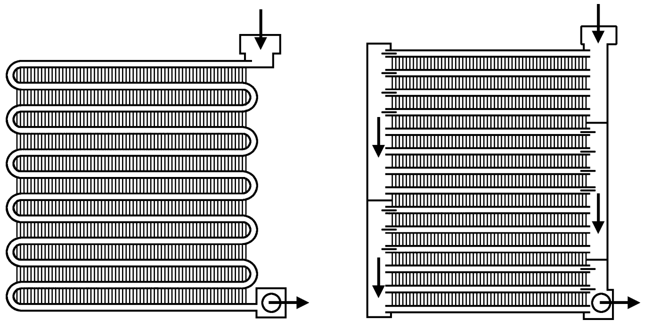

(A) SERPENTINE CONDENSER (B) PARALLEL-FLOW CONDENSER

Fig. 6 Basic Automotive Condensers
(Mathur 1999b)

Condenser. Automotive condensers are generally of the following designs: (1) tube-and-fin with mechanically bonded fins; (2) serpentine tube with brazed, multilouvered fins; or (3) header extruded tube brazed to multilouvered fins, also known as parallel-flow (PRF) condensers, which are primarily used in automotive applications (Figure 6). To prevent air bypass, condensers generally cover the entire radiator surface. Aluminum is popular for its low cost and weight.

Operation of Parallel-Flow Condenser. A PRF condenser consists of flat tubes that have multiple flow channels. Refrigerant is supplied directly to the tubes through the header. Louvered fins are currently used in automotive heat exchangers. A typical refrigerant tube has 0.08 in. thick wall with tube widths ranging from 0.71 to 0.87 in., with 6 to 12 flow channels; smaller tubes are also available. Flat tubes have less projected frontal area to the airstream; this results in lower air-side pressure drop. Performance of a parallel-flow condenser is superior to that of a serpentine condenser (Mathur 1998a), because the refrigerant is distributed in multiple tubes. For the same reason, refrigerant pressure drop in a PRF condenser is also much smaller.

Typically, in a PRF condenser, the first pass (see Figure 6B) has the largest number of refrigerant tubes, with fewer tubes in each successive pass. This is because the specific volume of superheated vapor coming out from the compressor is very large, and the density of refrigerant vapor is very small. This results in very high vapor velocities ($m = \rho AV$) in the tubes. At this condition, the refrigerant void fraction is unity, which results in a very high pressure drop. Therefore, this high volumetric flow must be subdivided into a large number of tubes to lower refrigerant velocities, and thus pressure drop. At some point along the condenser, refrigerant vapor temperature equals saturated temperature, and wall temperature falls below saturation temperature. At this time, condensation starts and the average density of the two-phase refrigerant mixture starts to increase. With the increase of the two-phase mixture density, the average refrigerant velocities start to decrease. This affects the condensation heat transfer coefficient and frictional pressure drop. When all vapors are condensed, the refrigerant flow becomes single-phase liquid. At this condition, the refrigerant flow velocity is lowest, which yields lower pressure drop. Thus, the last pass has the fewest tubes.

Condenser Design. Condensers must be properly sized. An undersized condenser results in high discharge pressures that reduce compressor capacity, increase compressor power requirements, and result in poorer discharge air temperatures. When the condenser is in series with the radiator, the air restriction must be compatible with the engine cooling fan and engine cooling requirements. Generally, the most critical condition occurs at engine idle under high-load conditions. An undersized condenser can raise head pressures sufficiently to stall small-displacement engines.

An oversized condenser may produce condensing temperatures significantly below the engine compartment temperature. This can result in evaporation of refrigerant in the liquid line where the liquid line passes through the engine compartment (the condenser is ahead of the engine and the evaporator is behind it). Engine compartment air has been heated not only by the condenser but by the engine and radiator as well. Typically, this establishes a minimum condensing temperature between 10 and 30°F above ambient. Liquid flashing occurs more often at reduced load, when the liquid line velocity decreases, allowing the liquid to be heated above saturation temperature before reaching the expansion valve. This is more apparent on cycling systems than on systems that have a continuous liquid flow. Liquid flashing is audibly detected as gas enters the expansion valve. This problem can be reduced by adding a subcooler or additional fan power to the condenser.

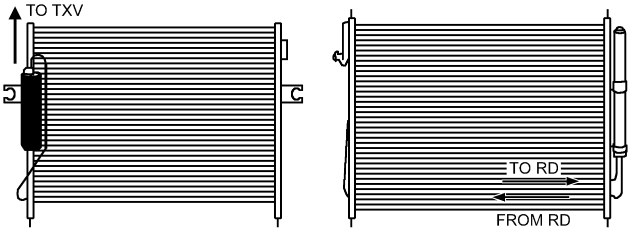
Internal pressure drop should be minimized to reduce compressor power requirements. Condenser-to-radiator clearances as low as 0.25 in. have been used, but 0.5 in. is preferable. Primary-to-secondary surface area ratios vary from 8:1 to 16:1. Condensers are normally painted black so that they are not visible through the vehicle's grille.

Placing the condenser ahead of the engine-cooling radiator not only restricts air but also heats the air entering the radiator. Air conditioning increases requirements on the engine-cooling system, which requires an increase in either radiator capacity, engine-cooling airflow, or both. Radiator capacity can be increased by adding fins, depth, or face area or by raising pump speed to increase coolant flow. Increasing coolant velocity is not normally done because it may cause excessive tube erosion or cavitation at the coolant pump inlet. With this configuration, engine-cooling airflow requirements increase; they are met by increasing fan size, number of blades, blade width, blade pitch, by the addition of a fan shroud, or a combination of these items. Increases in fan speed, diameter, and pitch raise the noise level and power consumption. For engine-driven fans (primarily used on trucks), temperature- and torque-sensitive drives (viscous drives or couplings) or flexible-blade fans reduce the increases in noise that come with the higher power. Virtually all automobiles rely on airflow produced by the forward motion of the car to reduce the amount of air the engine-cooling fan must move to maintain adequate coolant temperatures. As vehicle speed increases, fan requirements drop, and electric fans are deenergized or engine-driven fans are decoupled by the action of the viscous drive.

Because each vehicle is optimized for its intended market segment, some vehicles have a side-by-side condenser and radiator, each with its own motor-driven fan. This eliminates the effect of the condenser on the engine cooling air inlet temperature but causes other issues with fan control and potential engine bay recirculation when one system is energized and the other is not.

Subcooled Condensers. There is a trend of using subcooled condensers to improve overall air-conditioning system performance. Thermodynamically, by increasing subcooling at the end of the condenser (on a *p-h* diagram), the overall system performance is increased (see Chapter 1 of the 2005 *ASHRAE Handbook—Fundamentals*), because the overall evaporator enthalpy difference (i.e., the difference in enthalpies between evaporator outlet to inlet) increases. Figure 7 shows a conventional PRF condenser in which refrigerant flows out from the condenser to the receiver-drier. In the subcooled PRF condenser, refrigerant from the second-last pass flows to the receiver-drier and then back to the condenser in the last path to subcool the refrigerant. In a subcooled PRF condenser, the size of the receiver-drier can be reduced because the condenser has more liquid refrigerant.

Hoses. Rubber hose assemblies are installed where flexible refrigerant transmission connections are needed because of relative motion between components (usually caused by engine rock) or where stiffer connections cause installation difficulties and noise transmission. Refrigerant permeation through the hose wall is a design concern. Permeation occurs at a reasonably slow and predictable rate that increases as pressure and temperature increase. Hose with a nylon core (**barrier hose**) is less flexible, has a smaller OD, is generally cleaner, and allows practically no permeation. However, because it is less flexible, it does not provide damping of gas pulsations as does other hose material. It is recommended for R-134a.



(A) CONVENTIONAL SYSTEM (B) SUBCOOLED SYSTEM

Fig. 7 Conventional and Subcooled PRF Condenser Designs

Reducing Noise and Vibration. Typically, the refrigerant lines connected to the compressor (both suction and discharge sides) require hose that is a composite of rubber, nylon, and aluminum tube. This is necessary to eliminate or reduce transmission of clutch engagement noise to the cabin by metallic tubes. In some cases, mufflers are also used to reduce noise and vibrations from refrigerant flow.

Suction and discharge hoses and high-pressure liquid lines have connections for charging ports, sensor, and for service. Brackets and clips are also attached to the hoses and refrigerant lines to position and support the AC lines.

Expansion Devices. Virtually all modern automobiles use either a thermostatic expansion valve (TXV) or an orifice tube (or both, for dual evaporator systems) as the expansion device (see Chapter 44 of the 2006 *ASHRAE Handbook—Refrigeration* for more on these devices). Schematics of systems that use these devices are provided in the Controls section.

Automotive TXVs operate in the same manner as those for commercial HVAC systems. Both liquid- and gas-charged power elements are common. Internally and externally equalized valves are used as dictated by system design. Externally equalized valves are necessary where high evaporator pressure drops exist. A bulbless expansion valve, usually block-style, that senses evaporator outlet pressure without the need for an external equalizer is now widely used. TXV systems use a receiver-drier-filter assembly for refrigerant and desiccant storage.

Because of their low cost and high reliability, orifice tubes have become increasingly popular with automotive manufacturers. Developing an orifice tube system requires that components be matched to obtain proper performance. The orifice tube is designed to operate at 90 to 95% quality at the evaporator outlet, which requires a suction line accumulator to protect the compressor from floodback and to maintain oil circulation. Because the orifice tube does not fully use the latent heat in the refrigerant systems, orifice-tube systems generally require higher refrigerant flow than TXV systems to achieve the same performance. However, an orifice tube ensures that the compressor receives a continuous flow of cool refrigerant from the accumulator, offering benefits in compressor durability over a TXV system. Orifice-tube systems use an accumulator-drier-filter for refrigerant and desiccant storage.

Receiver-Drier-Filter Assembly. A receiver-driver is installed in the AC loop on the high-pressure side downstream of the condenser. Several types of desiccant are used, the most common of which is spherical molecular sieves; silica gel is occasionally used. The unit typically has desiccant either in a bag or cartridge, or sandwiched between two plates. The receiver-drier (1) serves as a reservoir for refrigerant from part- to full-load operating conditions, (2) removes moisture from the system, (3) filters out debris headed for the TXV, and (4) only allows liquid refrigerant to enter the TXV

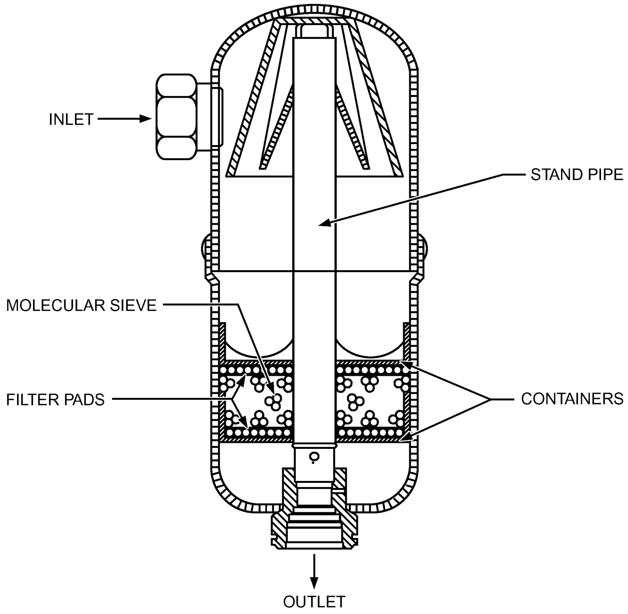


Fig. 8 Schematic of Typical Accumulator-Dehydrator

(liquid is removed from the top of the unit, and comes from the bottom via a tube connected to the top fitting).

The receiver-drier assembly accommodates charge fluctuations from changes in system load. It accommodates an overcharge of refrigerant to compensate for system leaks and hose permeation. The assembly houses the high-side filter and desiccant. Mechanical integrity (freedom from powdering) is important because of the vibration to which the assembly is exposed. For this reason, molded desiccants have not obtained wide acceptance. Moisture retention at elevated temperatures is also important. The rate of release with temperature increase and the reaction while accumulating high concentration should be considered. Design temperatures of at least 140°F should be used.

Receivers are usually (though not always) mounted on or near the condenser. They should be located so that they are ventilated by ambient air. Pressure drop should be minimal. Typically, a receiver-drier has a pressure switch or a pressure transducer installed that controls AC system operation at high pressure.

Suction Line Accumulators. A suction line accumulator is required with an orifice tube to ensure uniform return of refrigerant and oil to the compressor, to prevent slugging, and to cool the compressor. It also stores excess refrigerant. A typical suction line accumulator is shown in Figure 8. A bleed hole at the bottom of the standpipe meters oil and liquid refrigerant back to the compressor. The filter and desiccant are contained in the accumulator because no receiver-drier is used with this system.

Evaporator. The evaporator connects the air side of the air-conditioning system to the refrigerant side. Design aspects for the air side are discussed in the Air-Handling Subsystem section. The primary design consideration for the refrigerant side of the evaporator is low pressure drop. Because the evaporator operates at saturation, higher-pressure-drop evaporators cause nonuniform discharge temperatures unless they are designed with careful attention to pass arrangement. The space available in an automotive system does not allow for distribution manifolds and capillary tube systems outside of the evaporator envelope; this must be done within the evaporator itself.

Automotive evaporators must also mask the variation in compressor capacity that occurs with accelerating and decelerating. To avoid undesirable temperature splits, sufficient liquid refrigerant should be retained at the last pass to ensure continued cooling during acceleration.

High refrigerant pressure loss in the evaporator requires externally equalized expansion valves. A bulbless expansion valve, called a block valve, provides external pressure equalization without the added expense of an external equalizer. The evaporator must provide stable refrigerant flow under all operating conditions and have sufficient capacity to ensure rapid cooldown of the vehicle after it has been standing in the sun.

Auxiliary Evaporators. Many sport-utility vehicles, vans, and limousines are equipped with auxiliary or secondary air-conditioning modules located to cool rear-seat passengers. These system extensions provide some unique challenges. Most of these systems operate only when there are passengers in the rear space. Consequently, sometimes there is refrigerant flow through the primary ACM and none through the secondary. Careful attention should be paid to refrigerant plumbing to avoid refrigerant and oil traps in the suction line. The auxiliary suction line must never allow liquid oil to run downhill from the front system when there is no flow to carry it back to the accumulator-dehydrator. Designing highly efficient oil separators into the line set results in frequent compressor failure.

Refrigerants and Lubricants. The 1997 Kyoto Protocol identified the almost universally used R-134a as a global warming gas. This has led to a search for alternatives (Giles et al. 1997) among vehicle manufacturers and their suppliers. The leading contenders today are carbon dioxide (Bhatti 1997; Mathur 1998b, 1999c, 2000c, 2000d), hydrocarbon-based refrigerants (most concepts using a secondary coolant loop to keep the explosive refrigerant out of the passenger compartment) (Mathur 2001a, 2001b, 2003b), and ultralow-emission R-134a systems. Insufficient information exists to determine whether any one of these systems will be able to achieve the predominant position of R-134a today. Significant work has been done on carbon dioxide and hydrocarbons by OEMs and suppliers in North America, Europe, and Japan, and the Society of Automotive Engineers' (SAE) Interior Climate Control Committee has been developing multiple standards related to carbon dioxide. SAE also has held several conferences on alternative refrigerants. Vehicles with alternative refrigerant systems (CO_2 and hydrocarbons, both drop-in and with secondary loop systems) and baseline and enhanced R-134a (e.g., a suction line heat exchanger and oil separator) systems were tested for performance and comfort. Recently, Spatz (2006) proposed an alternative refrigerant, Fluid H, which has a very low global warming potential (GWP) and is nonflammable. Common polyalkylene glycol (PAG) lubricants have been used for conducting tests with this working fluid. Based on preliminary testing conducted on a vehicle, it is being proposed as a "drop-in" replacement refrigerant. Initial material compatibility evaluations did not reveal any issues.

New Vehicles. The phaseout of R-12 has led to the use of non-chlorofluorocarbon (non-CFC) alternatives in vehicles. The popular choice is R-134a because its physical and thermodynamic properties closely match those of R-12. Because its miscibility with mineral oil is poor, R-134a requires the use of synthetic lubricants such as PAG or polyol ester (POE). PAGs are currently preferred. These lubricants (especially PAGs) are more hygroscopic than mineral oil; production and service procedures must emphasize the need for system dehydration and limited exposure of the lubricants to atmospheric moisture.

Older Vehicles. Vehicles originally equipped with R-12 do not require retrofit to another refrigerant as long as an affordable supply of new or reclaimed R-12 exists. When circumstances require it, most air conditioners can be modified to use R-134a and POE. When PAG oil is used in a retrofit, the remaining mineral oil should be removed to levels established by the original equipment manufacturer to prevent residual chlorides from breaking down the PAG.

Several blends of two or more refrigerants are being sold as "drop-in" replacements for R-12. They should not be used without a thorough investigation of their effect on performance and reliability under all operating conditions. Other concerns include (1) flammability, (2) fractionation, (3) evaporator temperature glide, (4) increased probability of adding the wrong refrigerant or oil in future service, and (5) compounded complexity of refrigerant reclaim.

European Regulation of Mobile Air Conditioning. The EU directive (Vainio 2006) states that the phaseout of HFC-134a will start on January 1, 2011, for all new models. From January 1, 2017, no new vehicles sold in the EU can use HFC-134a or any fluorinated gas with a global warming potential higher than 150. Retrofitting vehicles with HFC-134a will not be allowed after January 1, 2011. Refrigerant leakage rates for single- and dual-evaporator AC systems have been defined as less than 40 and 60 g (1.4 to 2.1 oz), respectively. Using nonrefillable containers will no longer be allowed. This directive also covers the safety of the mobile air conditioners. All fluorinated gases covered by the Kyoto protocol will be recovered.

Enhanced R-134a Systems. SAE has initiated a program to improve the performance of existing R-134a systems. The goals are to (1) identify technologies to reduce mobile air-conditioning system R-134a refrigerant leakage by 50%, (2) improve R-134a mobile air-conditioning system efficiency [coefficient of performance (COP)] by 30%, (3) reduce vehicle soak and driving heat loads by 30% over current vehicles to reduce cooling requirements, and (4) reduce refrigerant loss during service and at end of life by 50%.

Advanced Technologies

HVAC suppliers are aggressively working on advancements for mobile HVAC to reduce energy consumption and improve thermal comfort for occupants. For instance, researchers are investigating using ventilated car seats to reduce air conditioning use and improve fuel efficiency without compromising thermal comfort (Lustbader 2005). Some other important technologies are as follows; Mathur (2004b) discusses them in greater detail.

Brushless Motors. These motors, used in some newer cars, are simpler than standard motors and are more reliable. Advantages include the following: (1) motor efficiency is higher, (2) commutation is accomplished electronically, (3) very high speeds and torque are possible without arcing, (4) thermal resistance is lower and the operating temperature range is thus wider, and (5) the absence of brushes reduces maintenance requirements and eliminates brush residue contamination of bearings or the environment. Because there is no brush arcing or commutation, brushless motors are much quieter, both electrically and audibly.

Positive-Temperature-Coefficient (PTC) Heaters. PTC heaters are small, ceramic-based heaters that use less energy and less time to heat more quickly than conventional units. They self-regulate at a preset temperature by regulating resistance to vary their wattage. Thus, their greater thermal dissipation results in higher efficiency. These systems are maintenance-free and very reliable. PTC heaters could be used in the HVAC system to hasten cabin heating during cold start-ups by providing heat to occupants until the engine is warm (Hauck 2003).

Smart Engine Cooling Systems with Electric Water Pumps (EWPs). These cooling systems use both an electric and mechanical water pump, or replace the mechanical water pump with a EWP (Wagner et al. 2003). Typically, an EWP system includes a 100 to 600 W electric pump, four-way water valve (Chanfreau et al. 2003), sensor, engine control management system, software, and a variable-speed radiator fan. At cold start-ups, allowing little or no flow to the radiator hastens engine warm-up, thus reducing emissions and improving fuel economy. Because the water (or coolant) temperature is precisely maintained, thermal stresses in the engine are less. Once the engine coolant is heated, this system can provide thermal comfort, even at idle or with the engine off, by pumping coolant through the heater core and running the blower.

42 V Systems. Energy requirements of modern vehicles have increased significantly as the needs of motors, actuators, and other electrical equipment have increased. Auto manufacturers are investigating using 42 V for high-load equipment (e.g., compressors, blower, condenser fans, PTC heaters, controls), and reserving the existing 12 V grid for lighting and other smaller-load accessories. This would improve air-conditioning system performance, because compressor speed would be independent of engine speed. These systems could be used for hybrid, electric, or fuel-cell vehicles.

MASS TRANSIT

This section discusses buses, rail cars, and fixed-guideway vehicles that transport large numbers of people. The air-conditioning systems for these vehicles generally use commercial components, and packaging may be specific to the application, often integral with the external styling. Weight, envelope, and power consumption are important factors. Power sources may be electrical (ac or dc), engine shaft, compressed air, or hydraulic. These sources are often limited, variable, and interruptible. Characteristics specific to each application are discussed in the following subsections. Design aspects common to all mass-transit HVAC systems include passenger comfort (ventilation, thermal comfort, air quality, expectation) and thermal load analysis (passenger dynamic metabolic rate, solar loading, infiltration, multiple climates, vehicle velocity, and, in urban applications, rapid interior load change).

VENTILATION AND THERMAL COMFORT

The requirements of ASHRAE *Standards* 55 and 62.1 apply for transportation applications, with special considerations, because passengers in transit have different perceptions and expectations than a typical building occupant. These considerations involve length of occupancy, occupancy turnover, infiltration, outside air quality, frequency and duration of door openings, personal preference, interior contamination sources such as smoking, and exterior contamination sources such as engine exhaust.

Typically, outside air ventilation between 5 and 10 cfm per passenger (at nominal passenger load conditions) is mechanically supplied at all times, although some variable-volume systems have been applied. Design load is defined by the specification documents. It may be based on the number of seats (for long distances) or also include a number of standees (for short distances), usually about 50% of the maximum standees possible. Measurement of CO_2 for air quality control is not practical in these applications because of extremely variable background CO_2 levels. The effective ventilation rate per passenger is generally somewhat higher than the nominal mechanical supply, and varies with the type of vehicle, length of ride, door openings, and average passenger occupancy. An important consideration is emergency ventilation when other systems fail; for example, the propulsion system may strand passengers in a situation where exit is not possible. Outside air dampers may be required by the procurement specification for emergencies.

The nature of the transit service may be roughly categorized by average journey time per passenger and interval between station stops, and this service type affects the necessary interior conditions within the vehicle. For example, a commuter rail passenger may have a journey time of an hour or more, with few stops. Passengers riding such service may remove heavy outer clothing before being seated. In contrast, a subway rider typically will not remove heavy clothing during a 10 min ride. Clothing and the environment from which passengers come, including how long they were exposed to those conditions and what they were doing (e.g., waiting for the train outdoors in the winter), are important factors in transit comfort. At the opposite extreme, most subway stations are not climate controlled, and often reach dry-bulb temperatures over 100°F in the summer. Thus, when boarding a climate-controlled vehicle, these passengers immediately perceive a significant increase in comfort. However, a passenger adjusts to a new environment in about 10 to 20 min; after that, the traditional comfort indices begin to apply, and the same interior conditions that were perceived as comfortable may now be perceived as less than comfortable. Before stabilization, a passenger may prefer higher-velocity air or cooler or warmer temperatures, depending to a certain extent on clothing. At the same time, other passengers may already have stabilized and have completely different comfort control desires. Therefore, the transit system designer is presented with a number of unusual requirements in providing comfort for all.

In addition to the effect on perceived comfort, the passenger's preboarding environment and activity also affect the system interior loads. Jones et al. (1994) evaluated the heat load imposed by people under transient weather and activity conditions as opposed to traditional steady-state metabolic rates. An application program, TRANMOD, was developed that allows a designer to predict the thermal loads imposed by passengers (Jones and He 1993). Variables are activity, clothing, wet- and dry-bulb temperatures, and precipitation.

European Committee for Standardization (CEN) *Standard* EN 13129-1 provides guidance in the area of railroad passenger comfort. Although this standard does not apply to countries outside the CEN, the information is valuable and may not be readily available elsewhere.

THERMAL LOAD ANALYSIS

Cooling Design Considerations

Thermal load analysis for transit applications differs from stationary, building-based systems because vehicle orientation and occupant density change regularly on street-level and subway vehicles and to a somewhat lesser degree on commuter and long-distance transportation. Summer operation is particularly affected because cooling load is affected more by solar and passenger heat gain than by outside air conditions. ASHRAE *Standard* 55 design parameters for occupant comfort may not always apply. Vehicle construction does not allow the low thermal conductivity levels of buildings, and fenestration material must have safety features not necessary in other applications. For these reasons, thermal loads must be calculated differently. Because main-line passenger rail cars and buses must operate in various parts of the country, the air conditioning must be designed to handle the national seasonal extreme design days. Commuter and local transit vehicles operate in a small geographical area, so only the local design ambient conditions need be considered.

The following cooling load components should be considered:

- Ambient air conditions for locations in North America and worldwide are given in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals.* For vehicles operating in an urban area, the heat island effect should be considered if the Handbook design values are derived from remote reporting stations. For subway car operation, tunnel temperatures should be considered.
- For vehicle interior comfort conditions, consult Figure 5 in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals.* Total heat gain from passengers depends on passenger activity before boarding the vehicle, waiting time, journey time, and whether they are standing or seated during the journey. Representative values are given in Table 1 in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals.*
- Ventilation air loads should be calculated using the method in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*, in the section on Infiltration and Moisture Migration Heat Gains. Air leakage and air entering during door dwell time should be taken into account.
- Interior heat includes that produced by the evaporator fan motor, inside lighting, and electrical controls.
- The vehicle's conductivity, in Btu/h·°F, should be provided by the vehicle designers. For the outside skin temperature, use the values in Table 15 in Chapter 29 of the 1997 *ASHRAE Handbook—Fundamentals*; the car design dry bulb should be used as the interior temperature.
- The instantaneous solar gain through the glazing should be calculated using summer midafternoon values and the glass shading coefficient. The direction of travel for this period of the day should be determined before using the solar heat gain factors listed in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*. The glass shading coefficient must be obtained from the window supplier.

The summer cooling analysis should be completed for different times of the day and different passenger densities to verify a reliable result. Cooling equipment capacity should consider fouling and eventual deterioration of heat transfer surfaces.

Heating Design Considerations

Winter outside design conditions can be taken from Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*. Interior temperatures can be taken from Figure 5 in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals*. During winter, conductivity is the major heat loss. The heat required to temper ventilation air and to counteract infiltration through the body and during door openings must also be considered.

Other Considerations

Harsh environments and the incursion of dirt and dust inhibit the efficiency of HVAC units. Specifications should include precise maintenance instructions to avoid capacity loss and compromised passenger comfort.

BUS AIR CONDITIONING

In general, bus air-conditioning systems can be classified as interurban, urban, or small/shuttle bus systems. Bus air-conditioning design differs from other air-conditioning applications because of climatic conditions in which the bus operates, equipment size limitations, and compressor rpm. Providing a comfortable climate inside a bus passenger compartment is difficult because the occupancy rate per unit of surface and volume is high, glazed area is very large, and outside conditions are highly variable. Factors such as high ambient temperatures, dust, rain, snow, road shocks, hail, and sleet should be considered in the design. Units should operate satisfactorily in ambient conditions from –22 to 122°F.

Ambient air quality must also be considered. Air intakes are usually subjected to thermal contamination from road surfaces, condenser air recirculation, or radiator air discharge. Vehicle motion also introduces pressure variables that affect condenser fan performance. In addition, engine speed governs compressor speed, which affects compressor capacity. R-134a is the current refrigerant of choice, but some units operate with refrigerants such as R-22 or R-407C.

Bus air conditioners are initially performance-tested as units in a climate-controlled test cell. Performance tests encompass unit operation at different compressor speeds to make sure the compressor performance parameters (e.g., unit operation at maximum ambient conditions, minimum ambient condition, TXV sizing, oil return and vibration/shock) are within boundaries. In addition, individual parts that make the unit should be qualified before use. Larger test cells that can hold a bus are commonly used to verify installed unit performance. Pulldown tests previously known as the "Houston pulldown test" and the "White Book pulldown test" have been replaced by a test described in American Public Transportation Association (APTA) Standard Bus Procurement Guidelines.

Reliability and ease of maintenance are also important design considerations. All parts requiring service or regular maintenance should be readily accessible, and repairs should be achievable within a minimum time.

Heat Load

The main parameters that must be considered in bus air-conditioning system design include

- Occupancy data (number of passengers, distance traveled, distance traveled between stops, typical permanence time)
- Dimensions and optical properties of glass
- Outside weather conditions (temperature, relative humidity, solar radiation)
- Dimensions and thermal properties of materials in bus body
- Indoor design conditions (temperature, humidity, and air velocity)

The heating or cooling load in a passenger bus may be estimated by summing the heat flux from the following loads:

- Solid walls (side panels, roof, floor)
- Glass (side, front and rear windows)
- Passengers
- Engine and ventilation (difference in enthalpy between outside and inside air)
- Evaporator fan motor

Extreme loads for both summer and winter should be calculated. The cooling load is the most difficult load to handle; the heating load is normally handled by heat recovered from the engine. An exception is that an idling engine provides marginal heat in very cold climates. Andre et al. (1994) and Jones and He (1993) describe computational models for calculating the heat load in vehicles, as well as for simulating the thermal behavior of the passenger compartment.

The following conditions can be assumed for calculating the summer heat load in an interurban vehicle similar to that shown in Figure 9:

- Capacity of 50 passengers
- Insulation thickness of 1 to 1.5 in.
- Double-pane tinted windows
- Outdoor air intake of 400 cfm
- Road speed of 65 mph
- Inside design temperatures of 60 to 80°F and 50% rh
- Ambient temperatures for location as listed in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*

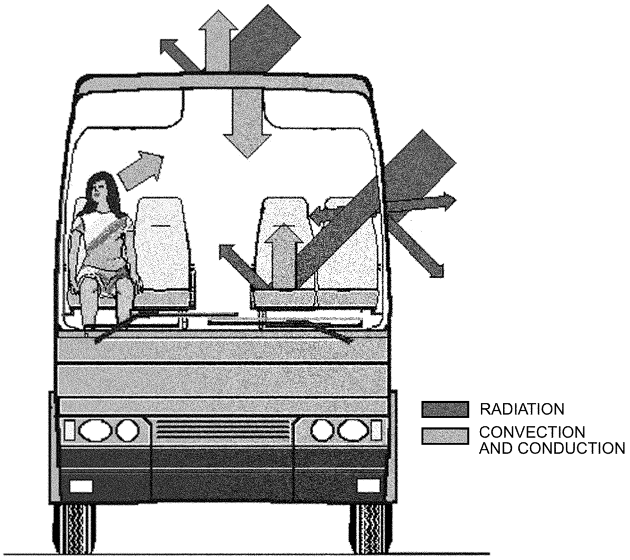


Fig. 9 Distribution of Heat Load (Summer)

Loads from 3.5 to 10 tons are calculated, depending on outside weather conditions and geographic location. The typical distribution of the different heat loads during a summer day at 40° north latitude is shown in Figure 10.

Air Distribution

Air-conditioning units are configured to deliver air through ducts to outlets above the windows or to act as free-blow units. In the case of free-blow units, louvers guide the air distribution inside the bus.

Interurban Buses

These buses are designed to accommodate up to 56 passengers. The air-conditioning system is usually designed to handle extreme conditions. Interurban buses produced in North America are likely to have the evaporator and heater located under the passenger compartment floor. A four- or six-cylinder reciprocating compressor, in which some cylinders are equipped with unloaders, is popular. Some interurban buses have a separate engine-driven compressor, preferably scroll, to give more constant system performance. Figure 11 shows a typical air-conditioning arrangement for an interurban bus.

Urban Buses

Urban bus heating and cooling loads are greater than those of the interurban bus. A city bus may seat up to 50 passengers and carry a

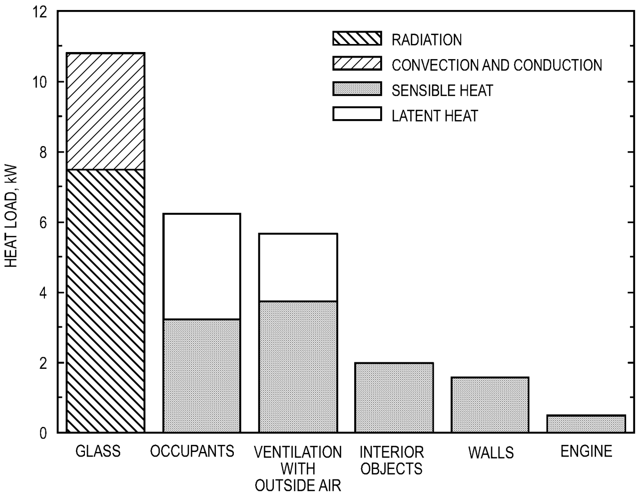


Fig. 10 Main Heat Fluxes in Bus

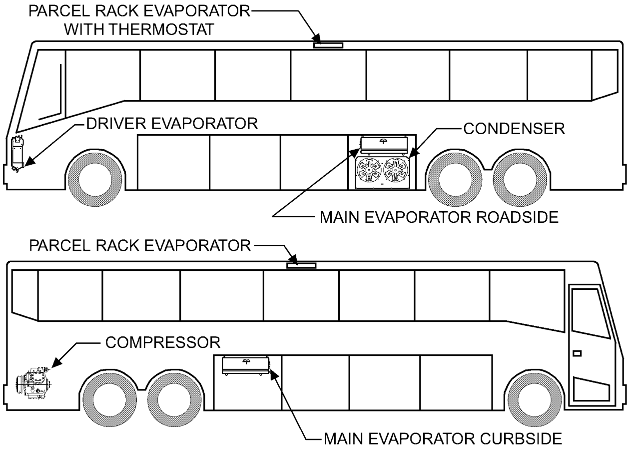


Fig. 11 Typical Arrangement of Air-Conditioning in Interurban Bus

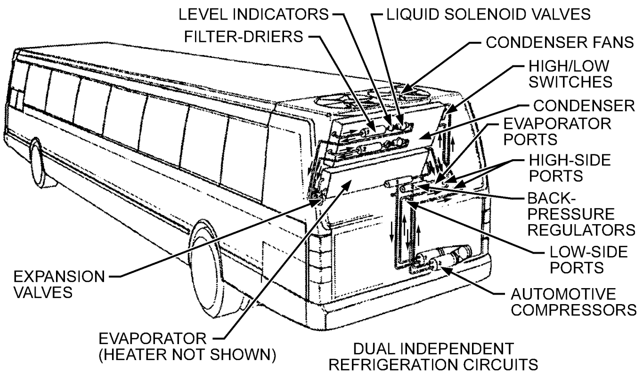


Fig. 12 Typical Mounting Location of Urban Bus Air-Conditioning Equipment

“crush load” of standing passengers. The fresh air load is greater because of the number of door openings and the infiltration around doors. Cooling capacity required for a typical 50-seat urban bus is from 6 to 10 tons. The buses are usually equipped with a roof- or rear-mounted unit, as shown in Figure 12. One or two compressors are usually belt- or shaft-driven from the propulsion engine. Capacity control is very important, because the compressor may turn more quickly than necessary at high engine speeds. Therefore, capacity control must compensate for not only the thermal load but also the engine-induced load. Cylinder unloaders are the primary means of capacity control, although evaporator pressure regulators have been use with non-unloading compressors, as shown in Figure 12. This configuration was used on buses produced between 1975 and 1995.

The heater is located just downstream of the evaporator. Hot coolant from the engine-cooling system provides sufficient heat for most operations; however, additional sources may be required in colder climates for longer idling durations. Additional floor heaters may also be required to reduce the effects of stratification. Conditioned air is delivered through overhead combination light fixture/diffuser ducts.

Low-profile rooftop-mounted units are used for either urban or interurban buses. They consist of the entire air-conditioning system except for the compressor, which is shaft- or belt-driven from the bus engine.

Small or Shuttle Buses

For small or shuttle buses such as those typically operating around airports or for schools, the evaporator is usually mounted in the rear and the condenser on the side or the roof of the bus. The evaporator unit is typically a free-blow unit.

Refrigerant Piping

Refer to Chapters 2 and 45 of the 2006 *ASHRAE Handbook—Refrigeration* for standard refrigerant piping practices. All components in the bus air-conditioning system are interconnected by copper tubing or refrigerant hose. When using copper tubing, care should be taken to analyze the effect of vibration on the tubing. Vibrational effects can be minimized by using vibration absorbers or other shock-cushioning devices. When using refrigerant hose, properties such as moisture ingression, effusion, maximum operating temperature, and burst pressure need to be taken into account. The refrigerant hose chosen should have the minimum amount of wax extractables on interaction with oil and the refrigerant.

Shock and Vibration

Most transport air-conditioning manufacturers design components for shock loading and vibrational inputs. Vibration eliminators, flexible lines, and other shock-cushioning devices interconnect the various air-conditioning components. The vibration characteristics of each component are different; in addition, the evaporator and the condenser must undergo individual vibration and shake tests. The input levels for the shake test can be based on the worst road conditions that the bus will encounter. This input level will vary because of the weight of the unit and its mounting.

System Safety

Per the U.S. Department of Transportation, all buses with air-conditioning systems operating in North America should conform to Federal Motor Vehicle Safety *Standard* (FMVSS) 302 for flammability standards. In addition, all evaporator units inside the vehicle should be mounted away from the head impact zone, as specified by FMVSS 222.

Controls

Most buses have a simple driver control to select air conditioning or heating. In both modes, a thermal sensing element (thermistor, mercury tube, etc.) controls these systems with on/off circuitry and actuators. Many systems use solid-state control modules to interpret the bus interior and outside ambient temperatures and to generate signals to operate full or partial cooling or heating functions. In these systems, thermistor temperature sensors are used, which are usually more stable and reliable than electromechanical controls. Control systems for urban buses can also include an outside-air ventilation cycle. The percentage of fresh air intake during the ventilation cycle can vary based on individual requirements.

RAIL CAR AIR CONDITIONING

Passenger rail car air-conditioning systems are generally electromechanical, direct-expansion units. R-22, a hydrochlorofluorocarbon (HCFC), has been the refrigerant most commonly used since the phaseout for R-12. R-134a, a medium-pressure refrigerant, has been used as a retrofit refrigerant in North America on systems originally designed to operate with R-12, and is commonly used in Europe for new equipment, mainly variable-speed screw compressors that are competitive in weight to R-22 reciprocating compressors. As HCFC refrigerants are phased out, the most likely replacements are hydrofluorocarbons (HFCs). R-407C is currently favored over R-410A because of the high condensing temperatures commonly found in transit applications. R-407C does have closely similar operating characteristics to R-22 and can, in many cases, be used as a replacement with minimal system changes.

Electronic, automatic controls are common, with a trend toward microprocessor control with increasing capability for fault monitoring and logging. Electric heating elements in the air-conditioning unit or supply duct temper outdoor air brought in for ventilation and are also used to control humidity by reheating the conditioned supply air during cooling partial-load conditions.

Air-cycle technology has been tested for passenger rail car air conditioning in Germany (Giles et al. 1997); however, issues of greater weight, higher cost, and low efficiency need to be addressed before it is widely accepted. Currently, there is no known research into using carbon dioxide or other transcritical refrigerants for transit. However, it seems likely that development of these systems for automotive use may lead to their use in bus applications, with possible expansion for other modes of transit.

Vehicle Types

Main-line intercity passenger rail service generally operates single and bilevel cars hauled by a locomotive. Locomotive-driven alternators or solid-state inverters distribute power via an intercar cable power bus to air-conditioning equipment in each car. A typical rail car has a control package and two air-conditioning systems. The units are usually either split, with the compressor/condenser units located in the car undercarriage area and the evaporator-blower portion mounted in the ceiling area, or self-contained packages mounted in interior equipment rooms. Underfloor and roof-mounted package units are less common in intercity cars.

Commuter cars used to provide passenger service from the suburbs into and around large cities are similar in size to main-line cars. Air-conditioning equipment generally consists of two evaporator-heater fan units mounted above the ceiling with a common or two separate underfloor-mounted compressor-condenser unit(s) and a control package. These cars may be locomotive hauled and have air-conditioning arrangements similar to main-line intercity cars, but they are often self propelled by high-voltage direct current (dc) or alternating current (ac) power supplied from an overhead catenary or from a dc-supplied third rail system. On such cars, the air conditioning may operate on ac or dc power. Self-propelled diesel-driven vehicles that use onboard-generated power for the air-conditioning systems still operate in a few areas.

Subway and **elevated rapid-transit cars** usually operate on a third-rail dc power supply. In the past, the air-conditioning system motors were commonly powered directly from the third-rail dc supply voltage. Most new equipment operates from three-phase ac power provided by a solid-state inverter. The inverter may be either an independent system or a component of the HVAC system. Split air-conditioning systems are common, with evaporators in the interior ceiling area and underfloor-mounted condensing sections, although unitary package units mounted on the roof or under the floor are increasingly popular.

Streetcars and **light-rail vehicles** usually run on ac or dc power transmitted via an overhead catenary wire, and have air-conditioning equipment similar to rapid-transit cars. Roof-mounted packages are used more often than undercar or split systems. This is largely because of the lack of undercar space. Figure 13 shows a typical configuration for these vehicles.

Equipment Design Considerations

Design considerations unique to transit HVAC equipment include the characteristics of the available power supply, weight limits, type of vehicle, and vehicle service parameters. Thus, ac-powered, semi-hermetic or hermetic compressors, which are lighter than open machines with dc motor drives, are a common choice. However, each car design must be examined in this respect because dc/ac inverters may increase not only the total weight, but also the total power draw, because of conversion losses.

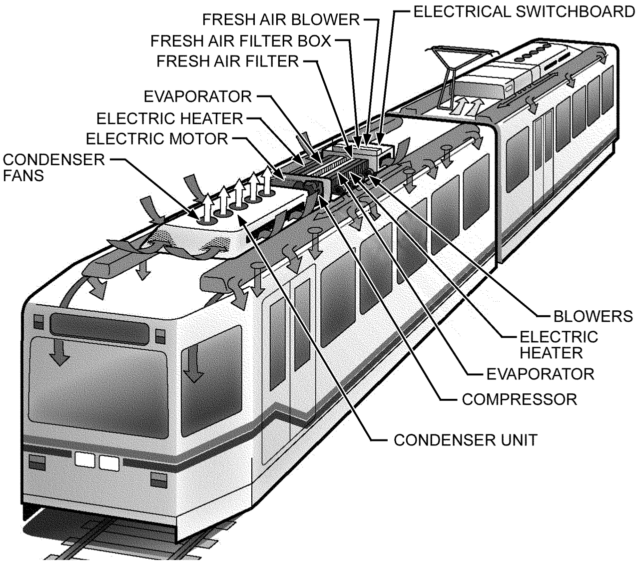


Fig. 13 Typical Light Rail Vehicle with Roof-Mounted HVAC System

Other concerns in equipment selection include the space required, location, accessibility, reliability, and maintainability. Interior and exterior equipment noise levels must be considered both during the early stages of design and later, when the equipment is coordinated with the car builder's ductwork and grilles.

Compressors. Reciprocating and vane compressors are commonly used, although scroll compressors are becoming increasingly popular. The scroll compressor is inherently more tolerant of flooded starts and liquid slugging common in the rail application than any other type of positive-displacement compressor. The low clearance volume of the scroll compressor allows it to operate at high discharge pressure more effectively than reciprocating compressors. Lower weight and less vibration and noise are benefits, as well. Screw compressors are also increasingly used (mostly in Europe), as are variable-speed compressor drives.

Power Supply Characteristics. Vehicles that draw their power from a stationary supply such as a third rail or overhead catenary wire are subject to frequent power interruptions as the train passes through gaps in the third rail or phase breaks in the overhead. These interruptions cause the HVAC equipment to shut down independently of the control system, and the design must take into account these losses of power and the subsequent need to restart the equipment. Vehicles that generate electrical power from an onboard source are less affected by power interruptions, although their capacity is limited. In either case, HVAC system control design must be coordinated with the vehicle's power supply and distribution system to avoid overloading vehicle systems during both steady-state and start-up (in-rush current) conditions. Additionally, it is desirable to prevent the vehicle's power supply from intentionally removing power from the HVAC equipment without an orderly shutdown sequence (including a pump-down cycle, if necessary).

Configuration and Space Constraints. Space underneath and inside a rail car is at a premium. Components are usually built to fit the configuration of the available space. Overall car height, roof profile, ceiling cavity, and wayside clearance restrictions often determine the shape and size of equipment.

Special Environmental Considerations. Dirt and corrosion constitute an important design factor, especially if the equipment is beneath the car floor, where it is subject to extremes of weather and severe dirt conditions. For this reason, corrosion-resistant materials and coatings must be selected. Aluminum has not proved durable in exterior exposed applications; the sandblasting effect tends to degrade any surface treatment on it. Because dirt pickup cannot be avoided, the equipment must be designed for quick and easy cleaning; access doors should be provided, and evaporator and condenser fin spacing is usually limited to 8 to 10 fins per inch. Closer spacing causes more rapid dirt build-up and higher cleaning costs. Dirt and severe environmental conditions must also be considered in selecting motors and controls.

Maintenance Provisions. Railroad HVAC equipment is subjected to mechanical shock and vibration during operation, is frequently required to operate under conditions of elevated condensing temperature and pressure, and is subjected to frequent on/off cycling because of power supply interruptions and other conditions that are not typical for a stationary application. As a consequence, the rail HVAC system's components are more highly stressed than equivalent components in a stationary system, and thus require more frequent maintenance and servicing. Because a passenger rail car with sealed windows and a well-insulated structure becomes almost unusable if the air conditioning fails, high reliability is important. Equipment design needs to consider the ease of routine service and time needed to diagnose and repair the system. The control equipment thus often incorporates monitoring and diagnostic capabilities to allow quick diagnosis and correction of a failure. However, many trains are designed with several individual vehicles permanently coupled together, in which case the failure of a single HVAC unit causes multiple cars to become unavailable for service while the

HVAC system is diagnosed and repaired. The time to diagnose and repair a system varies. Railroads, by their nature, are schedule driven, and varying, unknown repair time is incompatible with the need to provide scheduled service. Therefore, many users are moving away from fully on-car-serviceable air conditioners, and toward modular, self-contained units with hermetically sealed refrigerant systems. These units are designed for rapid removal and replacement to allow the vehicle to return to service in a short, predictable time. The faulty HVAC equipment is diagnosed and repaired off-car in a dedicated air-conditioning service area.

Safety. Security of the air-conditioning equipment attachment to the vehicle must be considered, especially on equipment located beneath the car. Vibration isolators and supports should be designed to safely retain the equipment on the vehicle, even if the vibration isolators or fasteners fail completely. A piece of equipment that dangles or drops off could cause a train derailment. All belt drives and other rotating equipment must be safety guarded. High-voltage controls and equipment must be labeled by approved warning signs. Pressure vessels and coils must meet ASME test specifications for protection of passengers and maintenance personnel. Materials selection criteria include low flammability, low toxicity, and low smoke emission.

Special Design Considerations. The design, location, and installation of air-cooled condenser sections must allow for the possibility of hot condenser discharge air recirculation into the condenser inlet (in the case of split systems), or into the outdoor air intakes (in the case of roof-mounted unitary systems), as well as the hot condenser discharge from trains on adjacent tracks that may occur at passenger loading platforms or in tunnels. To prevent a total system shutdown because of high discharge pressure, a capacity reduction control device is typically used to reduce the cooling capacity before system pressure reaches the high-pressure safety switch setting, thus temporarily reducing discharge pressure.

Even with coordination between the HVAC controls and the vehicle's power supply or distribution system, abrupt shutdown of the refrigeration system caused by power loss is common. The typical split-system arrangement places the compressor at or near the low point in the system. The combination of these factors results in undesired migration of refrigerant to the compressor during the off cycle. To reduce the likelihood of flooded compressor starts, using a suction line accumulator and crankcase heater is recommended.

Other Requirements

Most cars are equipped with both overhead and floor heat, typically provided by electric resistance elements. The control design commonly uses overhead heat to raise the temperature of the recirculated and ventilation air mixture to slightly above the car design temperature, while floor heat offsets heat loss through the car body. This arrangement is intended to limit stratification in the passenger compartment by promoting buoyant, convective air circulation. Times of maximum occupancy, outdoor ambient, and solar gain must be ascertained. The peak cooling load on urban transit cars usually coincides with the evening rush hour, and the peak load on intercity rail cars occurs in the midafternoon.

Heating capacity for the car depends on body construction, car size, and the design area-averaged relative wind-vehicle velocity. In some instances, minimum car warm-up time may be the governing factor. On long-distance trains, the toilets, galley, and lounges often have exhaust fans. Ventilation airflow must exceed forced exhaust air rates sufficiently to maintain positive car pressure. Ventilation air pressurizes the car and reduces infiltration.

Air Distribution and Ventilation

The most common air distribution system is a centerline supply duct running the length of the car between the ceiling and the roof. Air outlets are usually ceiling-mounted linear slot air diffusers. Louvered or egg crate recirculation grilles are positioned in the ceiling beneath the evaporator units. The main supply duct must be insulated from the ceiling cavity to prevent thermal gain/loss and condensation. Taking ventilation air from both sides of the roof line helps overcome the effect of wind. Adequate snow and rain louvers and, in some cases, internal baffles, must be installed on the outdoor air intakes. Separate outdoor air filters are usually combined with either a return or mixed air filter. Disposable media or permanent, cleanable air filters are used and are usually serviced every month. Some long-haul cars, such as sleeper cars, require a network of delivered-air and return ducts. Duct design should consider noise and static pressure losses.

Piping Design

Standard refrigerant piping practice is followed. Pipe joints should be accessible for inspection and, on split systems, not concealed in car walls. Evacuation, leak testing, and dehydration must be completed successfully after installation and before charging. Piping should be supported adequately and installed without traps that could retard the flow of lubricant back to the compressor. Pipe sizing and arrangement should be in accordance with Chapter 2 of the 2006 *ASHRAE Handbook—Refrigeration*. Evacuation, dehydration, and charging should be performed as described in Chapter 45 of that volume. Piping on packaged units should also conform to these recommendations.

Control Requirements

Rail HVAC control systems typically automatically transition between cooling and heating operation, based on interior and exterior dry-bulb temperature. The cooling and heating set points are generally different. This difference provides a control dead band to prevent the system from cycling directly between cooling and heating, and accommodates passengers' seasonal clothing. System capacity is matched to part-load conditions with some combination of evaporator coil staging, evaporator fan speed control, compressor cylinder unloading, or variable-speed compressor control in cooling mode, and staging or duty cycling of heat in heating mode. The control system typically does not consider latent heat information in the control algorithm, although reheat is commonly used to increase the apparent interior sensible load as the interior dry-bulb temperature falls below the desired cooling set point, to maintain humidity removal. Unitary systems may use hot-gas bypass for this purpose rather than electric reheat. If the interior dry-bulb temperature falls below the desired cooling set point, even with capacity reduction and reheat, the refrigeration system will shut down and the HVAC system will provide ventilation only. If the interior temperature drops to the heating set point, the system transitions to heating mode. Before the development of analog electronic or microprocessor control systems, this dry-bulb based control algorithm was implemented by banks of thermostats. This arrangement resulted in multiple, load-dependent interior set points as the system established quasi-equilibrium conditions within the dead band of each individual thermostat. When analog electronic controls were introduced in the early 1980s, they emulated this thermostat-based control algorithm, which is still often followed today in North America. Recently, several European and Asian HVAC manufacturers have introduced proportional-integral-derivative (PID) control systems, common in those markets for several years, to the North American market. Higher energy costs and greater environmental concern in Europe and Asia have led some manufacturers to include energy conservation algorithms in controls intended for use in those markets. The availability of robust, low-cost humidity sensors may lead to the use of latent heat information in control algorithms.

A pumpdown cycle and low-ambient lockout are recommended on split systems to protect the compressor from damage caused by liquid flooding the compressor and subsequent flooded starts. In addition, the compressor may be fitted with a crankcase heater that is energized during the compressor off cycle.

FIXED-GUIDEWAY VEHICLE AIR CONDITIONING

Fixed-guideway (FGW) systems, commonly called people movers, can be monorails or rubber-tired cars running on an elevated or grade-level guideway, as seen at airports and in urban areas. The guideway directs and steers the vehicle and provides electrical power to operate the car's traction motors (in some cases, the vehicle is propelled by a metal cable, driven by a motor mounted at the end of the guideway), lighting, electronics, air conditioner, and heater. People movers are usually unmanned and computer-controlled from a central point. Operations control determines vehicle speed, headway, and the length of time doors stay open, based on telemetry from individual cars or trains. Therefore, reliable and effective environmental control is essential.

People movers are usually smaller than most other mass-transit vehicles, generally having spaces for 8 to 40 seated passengers and generous floor space for standing passengers. Under some conditions of passenger loading, a 40 ft car can accommodate 100 passengers. The wide range of passenger loading and solar exposure make it essential that the car's air conditioner be especially responsive to the amount of cooling required at a given moment.

System Types

The HVAC for a people mover is usually one of three types:

- Conventional undercar condensing unit and compressor unit (which includes control box) connected with refrigerant piping to an evaporator/blower unit mounted above the car ceiling
- Packaged, roof-mounted unit having all components in one enclosure and mated to an air distribution system built into the car ceiling
- Packaged, undercar-mounted unit mated to supply and return air ducts built into the car body

Some vehicles are equipped with two systems, one at each end; each system provides one-half of the maximum cooling requirement. U.S. systems usually operate on the guideway's power supply of 460 to 600 V (ac), 60 Hz. Some newer systems with dc track power operate on 240 V (ac), 60 Hz from an inverter. Figures 14 and 15 show some arrangements used with fixed-guideway people mover vehicles, although similar arrangements could also apply to rail.

Refrigeration Components

Because commercial electrical power is available, standard semihermetic motor-compressors and commercially available fan motors and other components can be used. Compressors generally have one or two stages of unloaders, and/or hot-gas bypass is used to maintain cooling at low loads. Condenser and evaporator coils are copper tube with copper or aluminum fins. Generally, flat fins are preferred for undercar condensers to make it simpler to clean the coils. Evaporator/blower sections must often be designed for the specific vehicle and fitted to its ceiling contours. Condensing units must also be arranged to fit in the limited space available and still ensure good airflow across the condenser coil. R-22 is commonly used in these systems, although some newer systems use R-407C to meet environmental standards (zero ozone depletion potential).

Heating

Where heating must be provided, electric resistance heaters that operate on the guideway power supply are installed at the evaporator unit discharge. One or two stages of heat control are used, depending on the size of the heaters.

Controls

A solid-state control is usually used to maintain interior conditions. The cooling set point is typically between 74 and 76°F. For heating, the set point is 68°F or lower. Some controls provide humidity control by using electric heat. Between the cooling and heating set points, blowers continue to operate on a ventilation cycle. On rare occasions, two-speed blower motors are used,

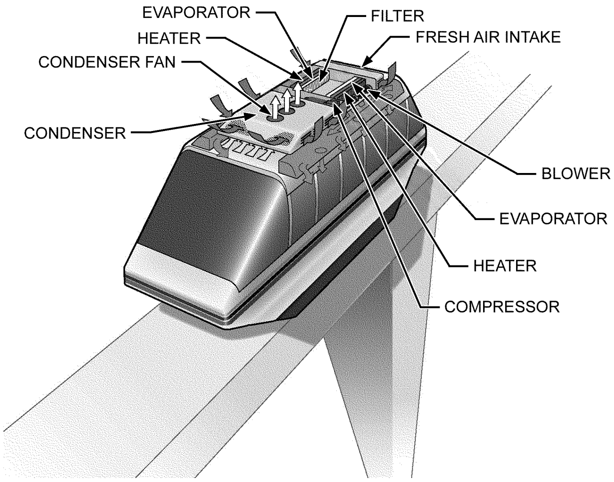
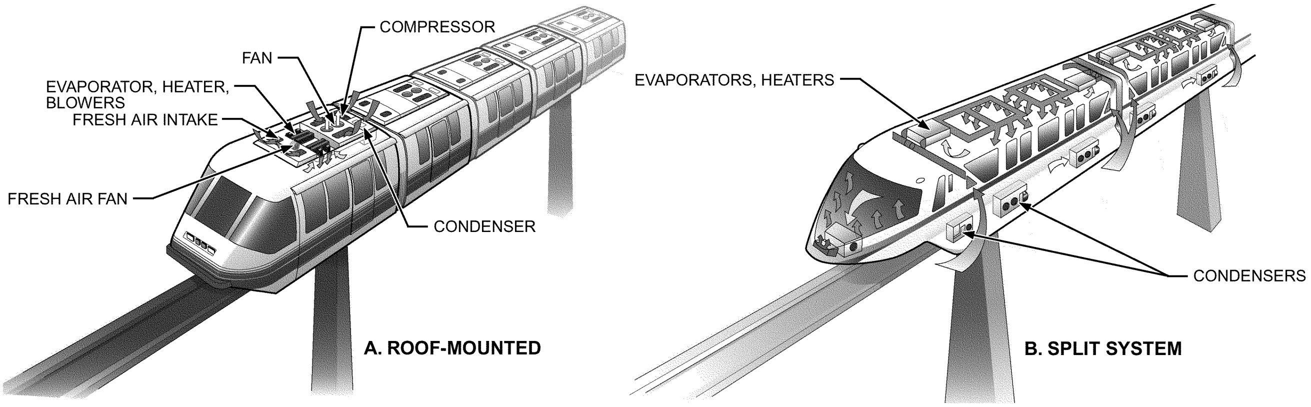


Fig. 14 Typical Small Fixed-Guideway Vehicle with Roof-Mounted HVAC System



A. ROOF-MOUNTED

B. SPLIT SYSTEM

Fig. 15 Example Monorail HVAC System Configurations

switching to low speed for the heating cycle. Some controls have internal diagnostic capability and can signal the operations center when a cooling or heating malfunction occurs.

Ventilation

With overhead air-handling equipment, outside air is introduced into the return airstream at the evaporator entrance. Outside air is usually taken from a grilled or louvered opening in the end or side of the car. Depending on the configuration of components, fresh air is filtered separately or directed so that the return air filter can handle both airstreams. For undercar systems, a similar procedure is used, except air is introduced into the system through an intake in the undercar enclosure. In some cases, a separate fan is used to induce outside air into the system.

The amount of mechanical outdoor air ventilation is usually expressed as cfm per passenger on a full-load continuous basis. Passenger loading is not continuous at full load in this application, with the net result that more outside air is provided than indicated. The passengers may load and unload in groups, which causes additional air exchange with the outside. Frequent opening of doors, sometimes on both sides at once, allows additional natural ventilation. The effective outside air ventilation per passenger is a summation of all these factors. Some older vehicles currently in service have no mechanical outside air supply. Newer vehicles have up to 9 cfm per passenger. Lower values of mechanical ventilation, typically 5 cfm or less per passenger, are associated with travel times of less than 2 min and large passenger turnover. Longer rides justify higher rates of mechanical ventilation.

Air Distribution

With overhead equipment, air is distributed through linear ceiling diffusers that are often constructed as a part of the overhead lighting fixtures. Undercar equipment usually makes use of the void spaces in the sidewalls and below fixed seating. In all cases, the spaces used for air supply must be adequately insulated to prevent condensation on surfaces and, in the case of voids below seating, to avoid cold seating surfaces. The supply air discharge from undercar systems is typically through a windowsill diffuser. Recirculation air from overhead equipment flows through ceiling-mounted grilles. For undercar systems, return air grilles are usually found in the door wells or beneath seats.

Because of the vehicle's typical small size and low ceilings, care must be taken to design the air supply so that it does not blow directly on passengers' heads or shoulders. High rates of diffusion are needed, and diffuser placement and arrangement should cause the discharge to hug the ceiling and walls of the car. Total air quantity and discharge temperature must be carefully calculated to provide passenger comfort.

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