Related Commercial Resources

CHAPTER 11. 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 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 underhood 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 the 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 underhood 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.

1. 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).

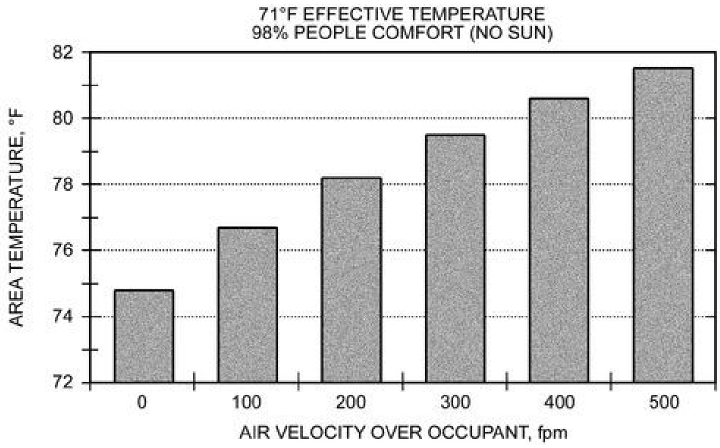

Figure 1. Comfort as Function of Air Velocity (Atkinson 2000. Reprinted with permission from SAE *Paper* 2000-01-1273. Copyright © 2000 SAE International.)

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 outdoor air (OA) extremely polluted, and it is important to ensure that passengers' exposures to these gases do not exceed American Conference of Governmental Industrial Hygienists (ACGIH 2014) 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) from unburnt fuel due to incomplete combustion
- Volatile organic compounds (VOCs) emitted from plastic parts, carpet, seats, headliner, door panels, etc.

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 vehicles alone account for 32% of HC emissions in the United States (Pearson 2001).

In winter, the HVAC unit is typically operated in outdoor air mode. Hence, there is a possibility of tailpipe emission entering the cabin in all heating modes (defrost, defrost-foot, and foot). To limit passengers' exposure to tailpipe emissions, the blower unit's air intake door can be switched from outdoor air mode to recirculation mode during times of traffic congestion and potential poor OA quality (Mathur 2006, 2018a). Once the vehicle is out of the traffic jam, the mode door can be switched back to outdoor air mode (Mathur 2007a).

Carbon dioxide (CO_2) from passenger exhalations can also build up in the cabin, especially in low-body-leakage or new vehicles, so the vehicle's A/C system should not be operated in recirculation mode for extended periods. This issue becomes critical when several occupants are in a vehicle that has 100% return air in recirculation mode. A timed strategy is recommended for recirculation; after the set time (e.g., 30 min) elapses, the mode automatically changes to outdoor to reduce CO_2 levels in the cabin. A CO_2 sensor can be installed to monitor levels in the cabin, and automatically switch to OA mode when set levels are exceeded (Mathur 2007b, 2008, 2009a, 2009b). Informative Appendix D of ASHRAE *Standard* 62.1-2016 specifies the suggested levels of carbon dioxide in conditioned space:

no more than 700 ppm over the ambient conditions for an extended period (for satisfaction of visitors entering a space, with respect to human bioeffluents [body odor]). Current global average ambient concentration level of CO_2, as of April 2018, is approximately 411 ppm (NOAA 2018). Hence, if the CO_2 concentration exceeds approximately 1100 ppm inside a vehicle cabin, then outdoor air must be introduced into the cabin to reduce the CO_2 concentration. This is especially crucial given that driver alertness and fatigue are impacted by CO_2 build-up (Mathur 2016b).

Partial Recirculation and Energy Efficiency. AC credits by U.S. EPA (2010) will encourage the OEMs to use strategy of using air in recirculation mode to improve energy efficiency. However, this will significantly affect the cabin air quality by an increase in CO_2 within the cabin. For vehicles running in recirculation mode for extended time may result in drowsiness of passengers and the occupants of the vehicle. This has been confirmed by some of the studies reported in SAE (Mathur 2019, 2020). Mathur (2019, 2020) has suggested a control strategy to limit the buildup cabin CO_2 per ASHRAE *Standard* 62. An experimental study conducted by Mathur (2016b) linked drivers fatigue due to the build-up of cabin CO_2 in recirculation mode.

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.

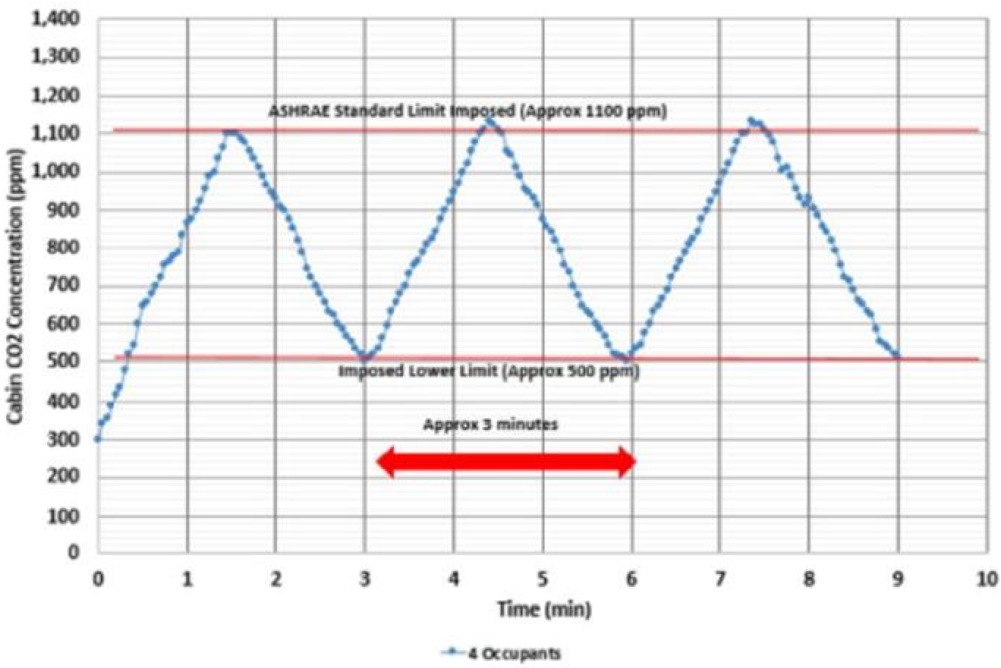

Figure 2. ASHRAE *Standard* 64 Imposed Data for Four Occupants at a Vehicle Speed of 40 kph

See the section on Controls under Air-Handling Subsystem 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 necessary.

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 compared to 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 the Society of Automotive Engineers (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. 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 of the southwestern United States. Achieving a comfortable interior temperature after a hot soak is usually one of the design conditions for most vehicle manufacturers.

Electric Vehicles and or autonomous vehicles have architecture different from a typical internal combustion engine vehicle. For such vehicles, we need to consider additional cooling loads. Autonomous vehicles and electric vehicles require a lot of computing power with multiple laptops worth computing power that will generate heat. We need to ensure that we address this additional cooling load.

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 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 tailwind 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 of 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 include bacteria, pollutants, vapors from vehicle fluids, and corrosive agents (Mathur 2006, 2017a). 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 can exceed 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).

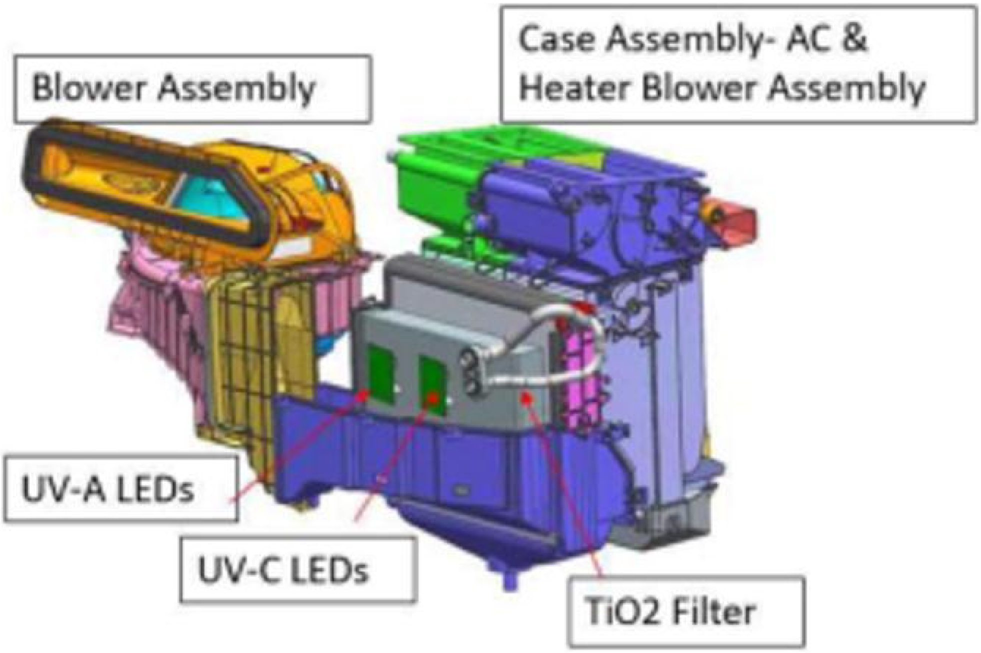

Figure 3. Isometric View of Developed HVAC Unit with UV and Titanium Dioxide Filter

UV based photocatalytic air purifier systems have been developed (Mathur 2021, 2022a) to eliminate living organic germs, bacteria, pathogens, etc. from the cabin air. In this system, the HVAC (Figure 3) unit has been developed by using a filter impregnated by titanium dioxide (TiO_2) with UV-C lights to improve and maintain cabin air quality. The designed system can be used for conventional vehicles, electric vehicles (EVs), ride sharing and for autonomous vehicles. The developed system is able to reduce the viruses by almost 99.99% (log 4 reductions) in first 20 minutes of unit operation.

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 for 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. For electric vehicles, power consumption from electric compressors and heaters (PTC heaters) is extremely important, because it directly affects driving distance (Jeffers et al. 2016).

Physical Parameters, Access, and Durability

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 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.

Automobiles also increasingly incorporate electrical and electronic components and functionality. This requires manufacturers to both limit the emissions of electrical signals from components and ensure that all components 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 always decreases 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 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 takes the path of least resistance, and if not forced over the heat exchangers, it usually bypasses them. In a good design, the condenser and radiator are the same size, and there should not be 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 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 is usually added atop the cross frame when the hood is closed. This prevents recirculation of the hot engine compartment air to approximately the top and bottom thirds of the condenser. Without this, condenser head pressure may increase greatly, further degrading system performance.

Active Grille Shutters: Active grille shutters have been used by some OEMs to improve system performance and to reduce drag on the vehicle. The grille shutter is placed in front of the radiator and the grilles can be opened and closed with a water sealed actuators. By closing the grilles the fuel economy is improved by reducing vehicle drag resistance. This system will allow airflow through the grille when demand on cooling system or air conditioning system is high. Under conditions of light load and moderate ambient temperatures and humidity, the grille does not have to be fully open. During winters, the grilles can be closed to speed up cabin heating. Hence, this system can be used to improve overall fuel economy and enhance system performance. These systems can also be used for electric vehicles to improve battery efficiency and driving range.

2. 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 subsystem. The evaporator core is a part of both the refrigeration and air-handling subsystems and links 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 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 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.

For electric vehicles, electric heaters (PTC heaters) are used instead of a conventional heater core. In some of these vehicles a high voltage water heater is used to provide heating for comfort and defrosting. These are discussed in the Advanced Technologies section of the chapter.

Heater Mode. Heater mode is designed to provide comfort heating to vehicle occupants. Typical maximum heater airflow is 125 to 200 cfm for a midsized 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 total airflow) 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 midsized 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.

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 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 midsized 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 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.

To maximize energy efficiency and cooling rate, the A/C system is typically operated in recirculation mode. However, in this mode, carbon dioxide exhaled by occupants remains within the cabin and can negatively affect cabin air quality (Atkinson et al. 2017; Mathur 2016b, 2017a, 2018b). Carbon dioxide increases. The carbon dioxide inhaled by occupants enters their bloodstreams, which may be detrimental to occupants' health. A timed strategy (about 10 min) is therefore recommended for recirculation. After this time, the mode automatically changes to OA to reduce CO_2 levels inside the cabin. A carbon dioxide sensor can also be used in the cabin to monitor levels. If it exceeds a predetermined level, the blower unit's intake door goes to OA mode (Mathur 2007a, 2007b, 2008).

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.

Outdoor 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 outdoor 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., controls for the ACM and 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, from the cable-controlled manual system to fully automatic systems that control the cockpit environment. The two main classifications are manual and automatic.

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 A/C 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 must 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 then varies the mix door position, air flow 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 available in many vehicles (Mathur 2007a, 2007b). Most of these systems assume that a vehicle quickly passes 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.

For auto control mode, not only we need to maintain thermal comfort for the occupants but also need to ensure we are meeting cabin indoor air quality per ASHRAE *Standard* 62. These include addressing particulate matters, various gases and viruses.

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 (i.e., 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 more power for 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 also serves several other functions, such as water separation, protection from snow ingestion, and gross filtration (usually through a screen).
- The air inlet plenum should also be located such that when the vehicle is covered by snow, the plenum still can furnish sufficient air to clear the windshield and provide fresh air to the occupants.

The air inlet plenum is usually located at base of the windshield. If properly sealed from 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 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 airstream, 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, powder like 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 airstream 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 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 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 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. Being able to direct the jet air and reach the occupants under all conditions can result in satisfied consumers; the lack of this ability has led to 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 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 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 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 various 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. Evaporators are typically treated with hydrophilic coating that prevents build-up of water within the evaporator fins and plates (Mathur 2016a, 2017b).

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, 2001, 2002, 2003).

Typically, an ACM is designed to provide the airflow required for 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. Heat gain from the vehicle and 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 liquid condensate be prevented from entering the vehicle interior, 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). Many cars that have plugged condensate drain holes have a distinct odor, which is given off by common organisms (present almost everywhere) that grow in warm, moist environments.

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 can significantly affect the drain system. 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 4) that combine all three functions into one component have been developed, but their design is complex. As shown in Figure 4, electric (PTC) heaters are used for the electric vehicles within the HVAC unit.

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.

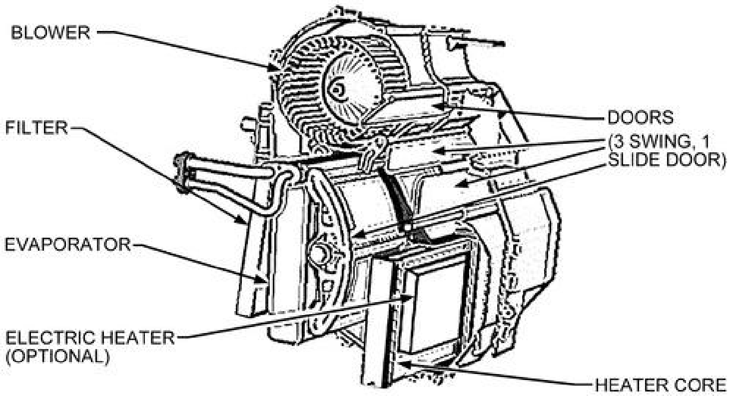

Figure 4. Integrated HVAC Unit

Reducing the noise, vibration, and harshness (NVH) characteristics of the interior has significantly improved comfort levels. During integration of the blower motor and fan into the module, pay careful attention 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, pay careful attention 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 is 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 outdoor 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 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 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 from rain, car washes, etc. It also provides the selection of either outdoor 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 is usually distributed 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 occupants.

Air Distribution. Air must be distributed in a way that minimizes pressure loss, thermal lag, and heat gain. Ductwork is usually designed around other underdash components, and frequently must follow a difficult path. 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.

Currently titanium dioxide (TiO_2) filters have been used in conjunction with UV-C lights to eliminate COVID-19 and other viruses from the cabin air (Mathur 2021, 2022a).

3. 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, 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 in 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.

4. REFRIGERATION SUBSYSTEM

Cooling is almost universally provided by a vapor cycle system. The thermodynamics of a vapor cycle system are described in Chapter 2 of the 2021 *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 trade-off 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 are shown in Figures 5 and 6. 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 maintains a minimum refrigerant density at the compressor's inlet, preventing overheating. Discharge air temperature is then increased, if necessary, by passing some (or all) of the evaporator outlet air through the heater core.

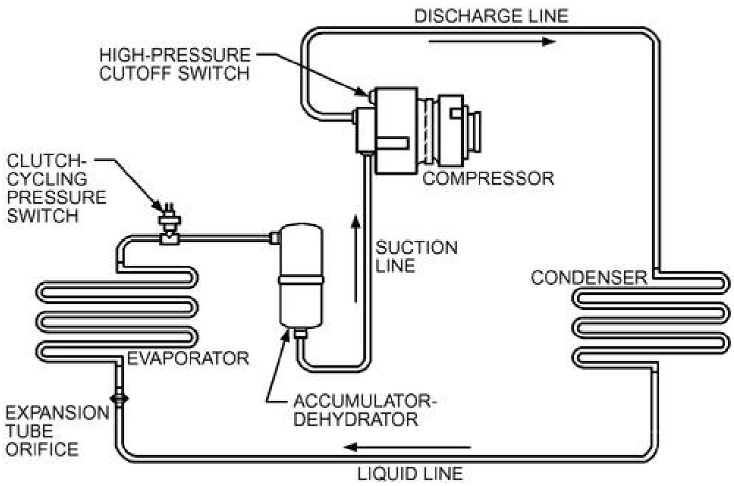

Figure 5. Clutch-Cycling System with Orifice Tube Expansion Device

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.

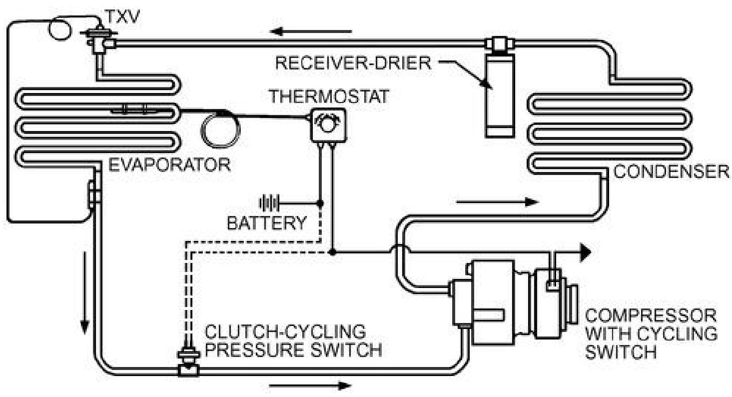

Figure 6. Clutch-Cycling System with Thermostatic Expansion Valve (TXV)

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 in 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 38 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*. Figure 7 illustrates basic automotive compressor types. The typical automotive compressor has the following characteristics:

- **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).
- **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 plate's angle. 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 (NVH).** 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.

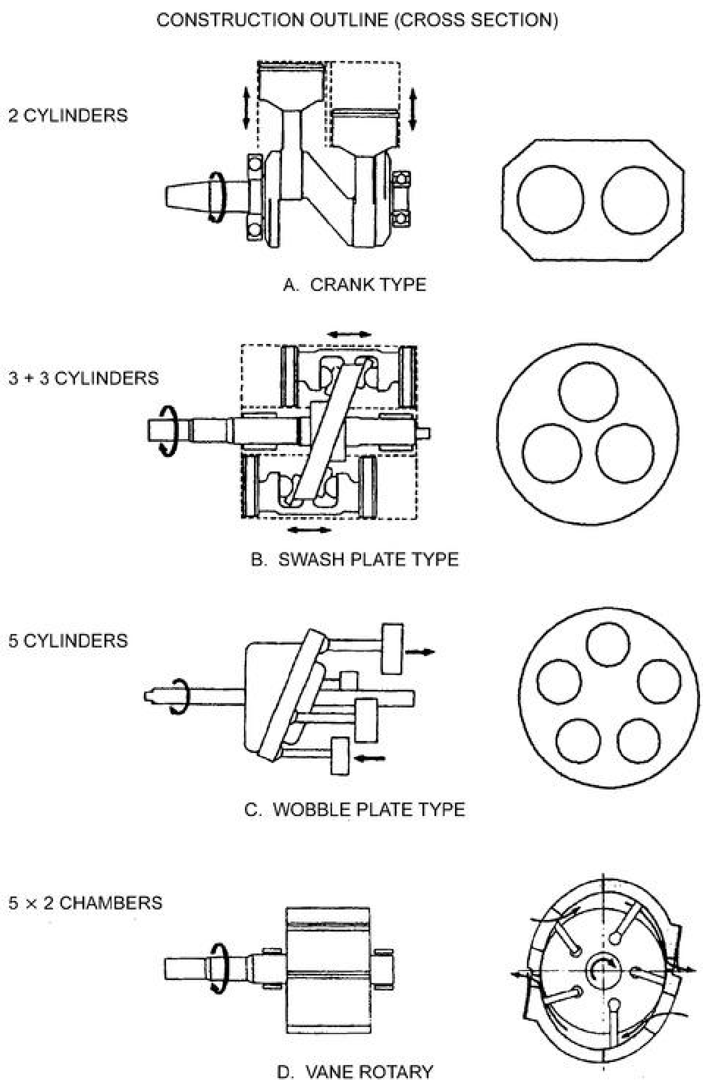

Figure 7. Basic Compressor Designs for Automotive Application

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 8). 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, which results in lower air-side pressure drop. Performance of a parallel-flow condenser is superior to that of a serpentine condenser (Mathur 1998), because the refrigerant is distributed in multiple tubes. For the same reason, refrigerant pressure drop in a PRF condenser is also much smaller.

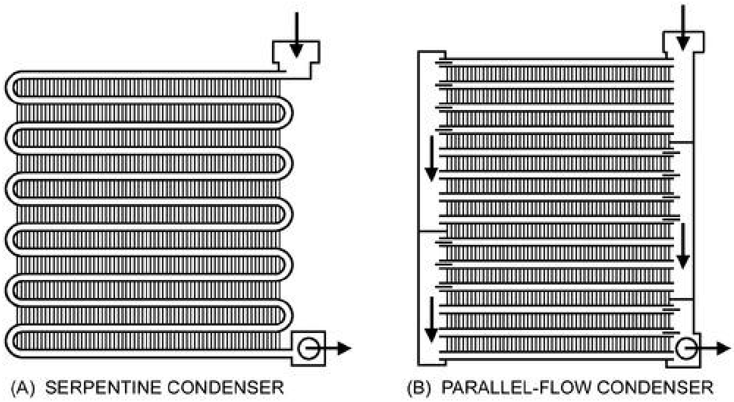

Figure 8. Basic Automotive Condensers (Mathur 1999b. Reprinted with permission from SAE *Paper* 1999-01-0236. Copyright © 1999 SAE International.)

Typically, in a PRF condenser, the first pass (see Figure 86B) 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 also by the engine and radiator. 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 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 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. Coolant velocity is not normally increased 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, or blade pitch; by adding a fan shroud; or by 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 car's forward motion 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 de-energized or engine-driven fans are decoupled by the action of the viscous drive.

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 2 of the 2021 *ASHRAE Handbook—Fundamentals*) because the overall evaporator enthalpy difference (i.e., the difference in enthalpies between evaporator outlet to inlet) increases. Figure 9 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.

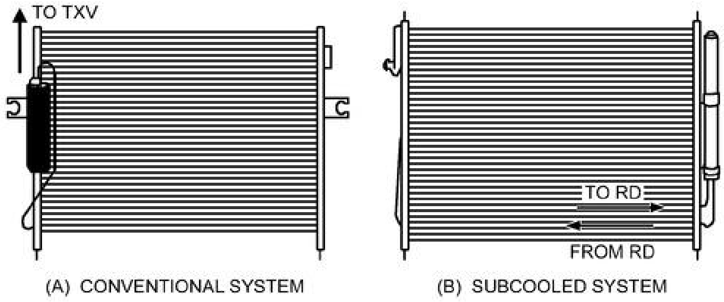

Figure 9. Conventional and Subcooled PRF Condenser Designs

Reducing Noise and Vibration. Typically, 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 A/C 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 11 of the 2022 *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.

Electronic Expansion Valves. For electric vehicles electronic expansion valves are used. These expansion valves have an electric actuator with a stepper motor to precisely control refrigerant flowrate through the system. The electric actuator controls the orifice area continuously to allow a higher or lower mass flow of refrigerant to pass, depending on the signals from the regulator.

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 A/C 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 (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. Consider the rate of release with temperature increase and the reaction while accumulating high concentration. Design temperatures should be at least 140°F.

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 A/C 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 10. 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.

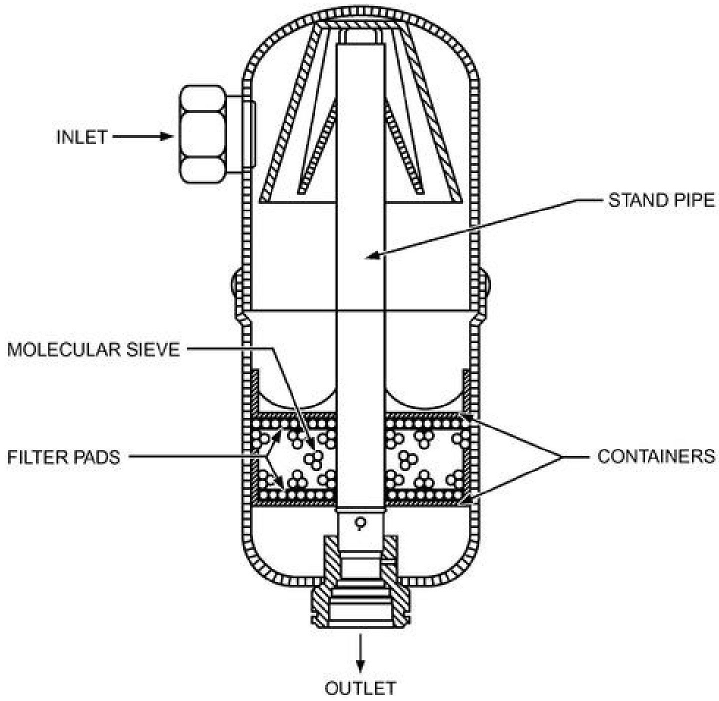

Figure 10. Schematic of Typical Accumulator-Dehydrator

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. Pay careful attention 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, sparking a search for alternatives among vehicle manufacturers and their suppliers. To address the global warming concerns of R-134a, some OEMs around the world have started using hydrofluoroolefin (HFO-1234yf) as a replacement for HFC-134a. HFO-1234yf offers a good combination of energy efficiency, safety, and ease of customer conversion. It has a global warming potential (GWP) of less than 1, which is 99.9% lower than HFC-134a, and is even less than CO_2 (GWP = 1). HFO-1234yf offers atmospheric lifetime and fuel efficiency benefits as well. This refrigerant has excellent environmental properties, low toxicity (similar to R-134a), and system performance similar to that of R-134a. It is being considered as a drop-in refrigerant for current mobile air-conditioning systems (MACS). Testing shows that both polyalkylene glycol (PAG) and polylol ester (POE) lubricants are compatible with HFO-1234yf in A/C systems with different types of compressors (Koban 2009; Spatz and Minor 2008, 2009). HFO-1234yf is being used by many OEMs globally, and as of December 2017, 45 million vehicles on the road used this refrigerant (Honeywell 2018).

Figure 11 compares R-134a and HFO-1234yf A/C cycles on the *p*-*h* diagram along with vapor density at suction temperatures (Spatz and Minor 2008). For HFO-1234yf, the latent heat of vaporization is lower and the vapor density at suction temperature is greater, compared to an R-134a system. Thus, for the same cooling capacity, the refrigerant mass flow rate for HFO-1234yf should be higher than in an R-134a system. Figure 12 compares the vapor pressures of the two fluids (Kontomaris and Leck 2009). Typical evaporating saturation pressures for HFO-1234yf are higher than for R-134a; HFO-1234yf pressure equals R-134a pressure at 100°F; and HFO-1234yf pressure is lower than R-134a above 100°F. Hence, in comparison to R-134a, a slightly higher evaporating pressure and slightly lower condensing pressure for HFO-1234yf reduces the pressure ratio, thereby improving system coefficient of performance (COP). Several OEMs and suppliers (Bang 2008; Mathur 2010a, 2010b, 2011a, 2011b, 2012, 2013, 2018a; Meyer 2008, 2009; Minor 2008) have conducted independent tests with HFO-1234yf. SAE also conducted tests with alternative refrigerants, including HFO-1234yf (Atkinson 2008), through cooperative research projects (Hill 2008).

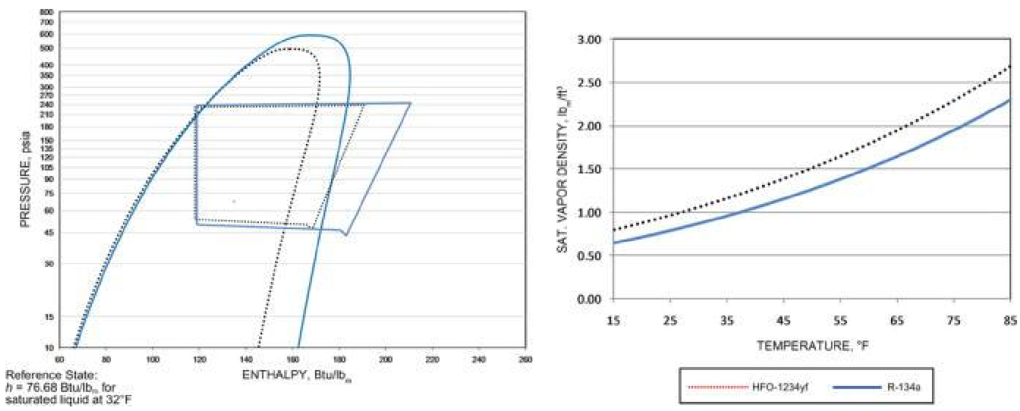

Figure 11. Comparison of Thermodynamic Cycle Between Base Case (R-134a) and HFO-1234yf (Spatz and Minor 2008)

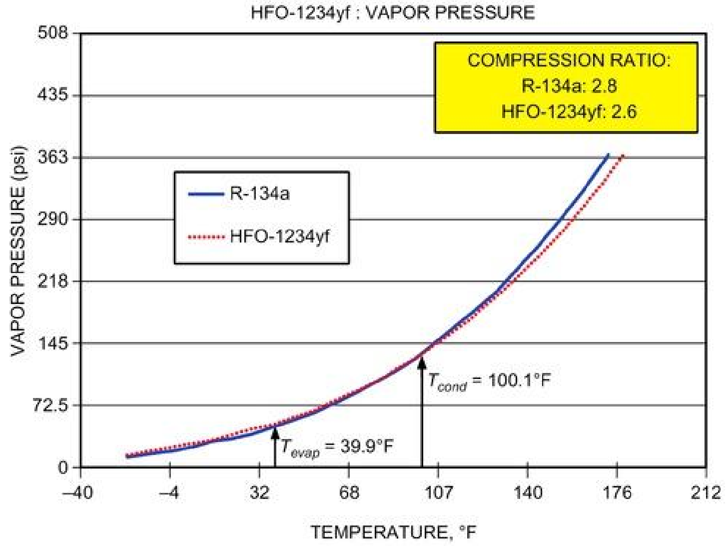

Figure 12. Comparison of Vapor Pressure Between Base Case (R-134a) and HFO-1234yf (Kontomaris and Leck 2009)

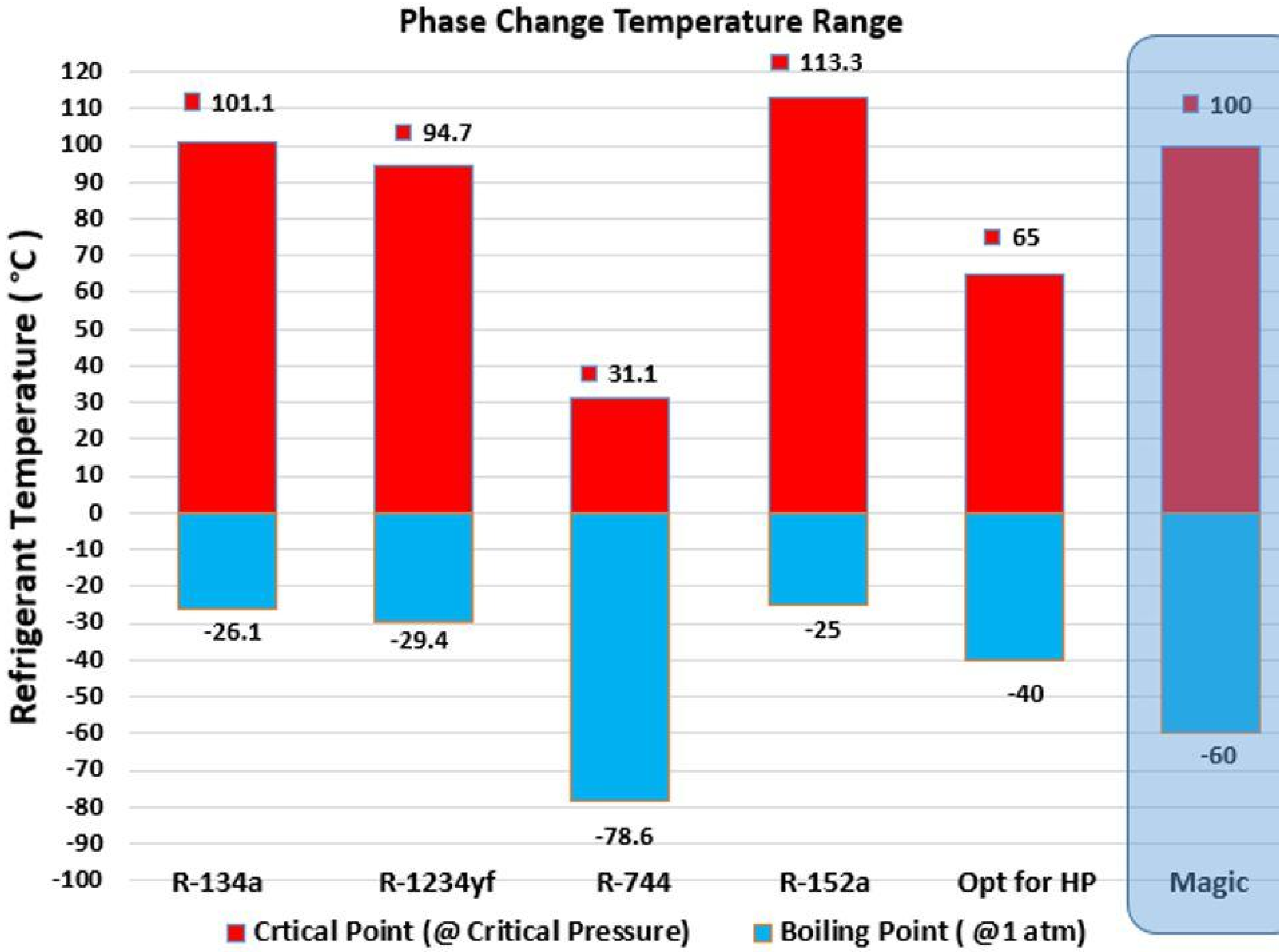

Figure 13. Comparison of the Refrigerant for Heating and Cooling. Need a Magic Molecule that Will Be Suitable for Heat Pump Application for Colder Climates

Refrigerants R-134a and HFO-1234yf have good performance for cooling mode. However, these refrigerant are not suitable for heat pump application. R-744 works well for the heating mode but has serious drawback when using this refrigerant for cooling mode. R-152a also has similar performance characteristics as R-134 and HFO-1234yf. However, this is a flammable refrigerant and can only be used in a secondary loop. This results in a reduced efficiency. Optimum operating temperature range for a heat pump application requires a refrigerant that has a critical temperature approximately of 100°C and a boiling point (at 1 atm) of below –60°C. SAE has established a research project to determine a new "magic" molecule (see Figure 13) that has a boiling point >= 100°C and a critical temperature <= –60°C. A technical committee has been formed and this committee is working (Patti 2022) with many refrigerant manufacturers globally.

Enhanced R-134a Systems. SAE 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 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%.

Suction Line Heat Exchanger. A/C system performance can be improved by adding a suction line heat exchanger into the system. This directly influences the thermal comfort for the occupant along with fuel economy and exhaust emissions. A suction line heat exchanger in an A/C loop (1) increases system performance, (2) subcools liquid refrigerant to prevent flash gas formation at inlets to the expansion valve, and (3) fully evaporates any residual liquid that may remain in the suction line before reaching the compressor. Performance of mobile air conditioning systems can be enhanced from 6 to 12% (Kurata et al. 2007; Mathur 2009c, 2011a).

Electric Vehicles and Heat Pump Systems. Due to stricter environmental regulations and higher fuel economy standards from the government, car manufacturers are investigating different options for fuel economy. One of the options is electrification of the propulsion system, resulting in significant gains in fuel economy and a reduction of global warming gases. Currently, a majority of car makers either already offer electric vehicles (e.g., Nissan Leaf, Tesla, GM Chevy Bolt, etc.) or have models in the process of design.

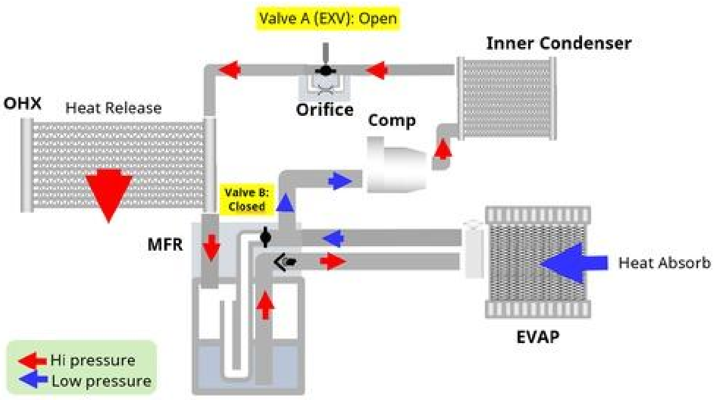

Figure 14. Heat Pump System in Cooling Mode

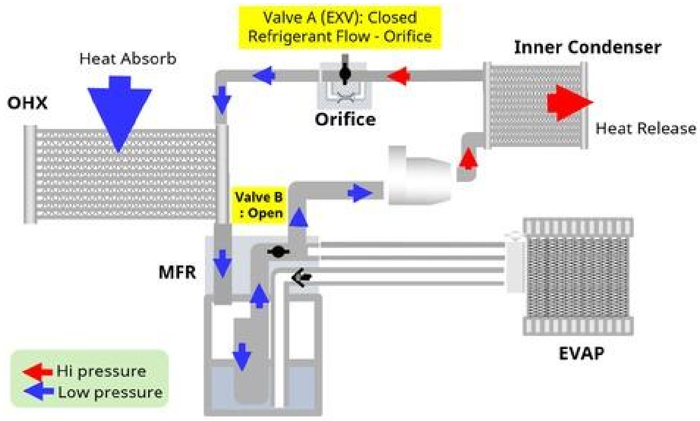

Figure 15. Heat Pump System in Cooling Mode (accumulator + EXV)

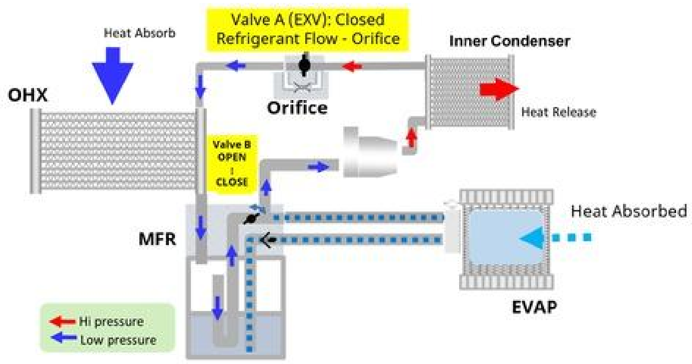

Figure 16. Heat Pump in Heating Mode with Dehumidification

Customers expect the same level of comfort in EVs as they are accustomed to in conventional vehicles. However, heating and/or cooling has a big influence on vehicle energy efficiency. For conventional vehicles, heating and cooling affects fuel economy, but waste heat from the engine is available for heating the cabin. EVs do not have this waste heat, so it is necessary to use electric positive temperature coefficient (PTC) heaters. Using a heat pump system along with a PTC heater consumes a significant amount of battery power that could severely limit the driving range of the EV.

Heat pump systems utilize a series of complex thermal management loops with sophisticated flow controls. Utilizing a series of refrigerant and coolant loops, heat pump system enhances energy efficiency for both powertrain thermal management and cabin comfort. The system currently targets battery electric vehicles (BEVs) with energy efficiency as main objective. While few systems are in production today, there is still lots to be learned about the technical challenges and the benefits from heat pump systems given their complex design, refrigerant consideration and control requirements to name a few.

Heat pump systems are employed for electric vehicles. One such system developed by Highly-Marelli (Mathur 2022b) takes advantage of the TXV and receiver drier (R/D) for cooling and accumulator and orifice for heating by using a multi-flow receiver (MFR). MFR has one inlet and two outlets. One outlet is for the providing high pressure subcooled liquid to the TXV in the cooling mode; and the second outlet provided low pressure saturated vapor to compressor suction during winter operation. This MFR act as a receiver drier for a TXV system during summer time when cooling is required; and act as an accumulator for an orifice system during winter time when heating is required. Hence, by using this MFR in a system, the HVAC system can essentially operate as a TXV-R/D as well as an orifice accumulator system. This developed system reduces the number of lines and joints in the system, thereby, decreasing the overall mass of the system. Since the system has less number of joints, the chances of refrigerant leakage through the joints are less. Lower amounts of the refrigerant lines results in a reduced system charge. Complex control strategy and valves are used to direct the refrigerant in the loop for heating and cooling operation.

This system consists of conventional heat exchangers in the system: (i) Outer heat exchanger (OHX) is mounted in front of the vehicle that act as a condenser and rejects heat to atmosphere during summer; and act as an evaporator to absorb heat from the atmosphere during winters; (ii) Evaporator inside of the HVAC unit that provides cooling and dehumidification by absorbing energy from the incoming air-stream during summer; and acts as an evaporator in heating mode for dehumidification during winters; (iii) Inner condenser (see additional details in advanced technologies section) inside of the HVAC unit to provide heating for comfort during winters but stays inactive during summer or cooling season; (iv) Multi-flow receiver (MFR) as described above; (vi) Electric compressor; (vii) Electronic expansion valves; (viii) Orifice.

Operating in Cooling Mode (Figure 14). In cooling mode, MFR acts as a TXV-receiver drier system. The high pressure vapor from the compressor outlet goes through valve A that is open into the condenser. Heat is rejected to the ambient and the sub-cooled liquid refrigerant goes into the MFR tank. For summer operation, valve B is closed forcing the liquid from the other leg into the evaporator through a TXV. Heat is absorbed by the two-phase refrigerant within the evaporator, providing cooling and dehumidification. The superheated refrigerant vapor is then fed into the compressor suction, completing the cycle. During summer operation, the inner condenser is inactive.

Operating in Heating Mode (Figure 15). In heating mode, MFR acts as a receiver. High pressure and high temperature refrigerant vapor from the compressor outlet goes first to the inner condenser to reject heat into the air to provide heating for comfort. The refrigerant changes its phase and transforms to liquid. This high pressure liquid then passes through an orifice with valve A in closed position. The two phase refrigerant enters the OHX where heat is absorbed from the atmosphere. The saturated vapor then flows into compressor suction through MFR, thereby, completing the cycle. Note that in this case only vapor is allowed into the compressor suction through the MFR that is now acting as an accumulator. The refrigerant vapor is then fed into the compressor suction, completing the cycle. Small amounts of refrigerant, just enough to dehumidify air, is intermittently (Figure 16) pumped into the evaporator. In this case the solenoid for valve B opens and closes approximately three times a minute. This also helps improve energy efficiency.

Operating in Dehumidification and Heating Mode (Figure 16). In heating mode, the MFR acts as a receiver. High pressure and high temperature refrigerant vapor from the compressor outlet goes first to the inner condenser to reject heat into the air to provide heating for comfort.

This is a direct heat pump system. For indirect heat pump systems, with waste heat recovery, the inner condenser is replaced by a water cooled condenser that delivers the waste heat into the HVAC unit for comfort heating.

5. 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.

Micro Climatic Zone for Heating and Cooling. In a conventional vehicle, the entire cabin is conditioned to comfort conditions based on the set point decided by the driver. Maintaining a certain cabin temperature in winter or summer uses significant energy. Typically, for a midsized sedan, the total airflow through the HVAC unit is 318 cfm for cooling and 212 cfm for heating. In the United States, a vast majority of the vehicles are driven with only one occupant. In a conventional vehicle, the entire cabin has to be conditioned, even when only a single person is inside of the vehicle. Many companies (OEMS and suppliers) have been developing new concepts for heating and cooling by creating “micro-zones” for cooling and heating. The objective is to reduce energy consumption by providing thermal comfort to occupants on an individualized basis. In this case, the total airflow required per person to create microzones is about 15 cfm per person. Therefore, for a vehicle with four occupants, the total airflow will be 120 cfm, which is 38% of the total cabin airflow rate. This approach is extremely useful for EVs, because the HVAC energy consumption directly affects the vehicle’s driving range. **Ventilated seats** are also used by some OEMs to create microzones to provide quick thermal comfort to occupants (Berry et al. 2017; Morishita et al. 2018).

Engine Start/Stop Feature for Energy Efficiency. In recent years, start/stop systems have been widely adopted for various vehicles as a countermeasure to environmental problems caused by automobiles and to improve fuel economy. Stoppage at a red light can be 30 to 60 s; in some countries, the red light duration may be longer. According to a recent survey (Autobeat 2018), 70% of the vehicles produced in the United States will have this feature within the next 5 years. On such vehicles, air conditioner compressors driven by an engine stop when the vehicle stops at a traffic signal. As a result, comfort of occupants deteriorates because of a rise in air temperature from the A/C outlets (Uematsu et al. 2015). On the other hand, if the engine is started at a traffic signal to improve occupant comfort, the fuel economy deteriorates. To best support passenger comfort while the engine is stopped, the HVAC system should be able to continue providing thermal comfort. This can be accomplished using the following systems:

- *Secondary loop.* A secondary loop cooling system incorporates two different working fluids to provide cooling. In all systems, the primary loop is a traditional direct-expansion design that uses a phase-change refrigerant (e.g., R-134A) and a compressor to circulate the refrigerant (Ghodbane 2000; Ghodbane et al. 2007; Menken et al. 2016). Figures 5 and 6 are both schematics for traditional direct-expansion systems. A heat exchanger is used to transfer energy from the primary loop to the secondary loop, which is called a chiller (Figure 17). In most applications, the working fluid in the secondary loop is a single-phase fluid that is circulated by a pump to the cooling coil. This cooling coil is placed in the HVAC unit. Note that, in a secondary system, the heat exchanger in the HVAC is called a cooling coil (not an evaporator), given this is a single-phase fluid circuit. Typically, automotive coolant is used as the working fluid. The secondary fluid absorbs energy as the hot air passes through the cooling coil. Figure 17 is a schematic representation of this type of secondary loop. The cooled fluid is circulated in the HVAC unit through a coil that provides cold air to the cabin. The size of the chiller depends on vehicle stoppage times.
- *Evaporators with Phase-Change Materials (PCMs).* Currently, cool-storage evaporators are used on many vehicles to continue providing thermal comfort to the occupants during stops at traffic signals (LaClair et al. 2016; Sato et al. 2016). The cool-storage evaporator prevents temperature increase both of air through vents and of the cabin when the engine (and consequently the A/C compressor) stops. In cool-storage evaporators, some of the plates have phase-change material that stores the energy at cold temperatures. During a vehicle stoppage, the evaporator continues to provide thermal energy from the phase-change material. Figure 18 shows a cool storage evaporator (Morishita et al. 2018) that has five plates containing the phase-change material. These plates are stacked inside the evaporator so that the cold energy stored in these five plates, along with the aluminum heat exchanger, can be used to continue providing thermal comfort to occupants while the engine is off. Evaporators with thermal storage materials have been investigated for idle start/stop function (Automotive Engineering 2012). Many researchers have been conducting research on improvement of heating in electric vehicles using phase-change materials.

Brushless Motors. These motors 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.

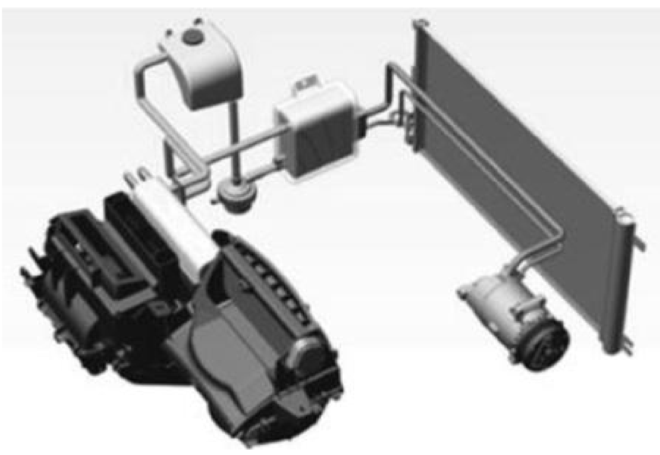

Figure 17. Automotive HVAC Unit with a Secondary Loop (Ghodbane 2000)

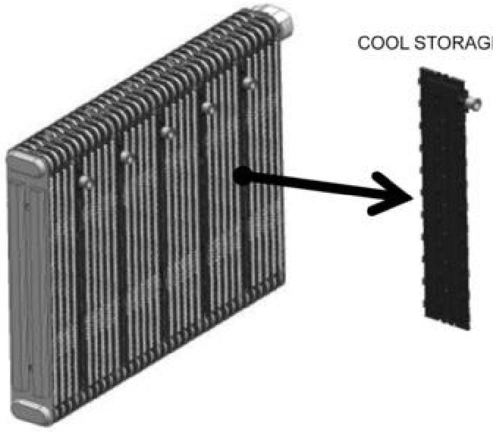

Figure 18. Energy Storage Evaporator (Morishita et al. 2018)

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).

Thermoelectric Devices. Thermoelectric devices (TEDs) are used to help create microzones to provide thermal cabin comfort. These devices work using the Peltier effect, wherein a voltage is applied between two wire joints with dissimilar materials. These devices are placed inside seats to provide quick thermal comfort to occupants (Arsie et al. 2014).

Water-Cooled Condensers. Water-cooled condensers are being investigated by OEMs and suppliers to reduce costs and space required for rejecting engine heat (Mathur et al. 2012). The advantage of this system is that a water-cooled condenser can be placed at any location, rather than just the front of the vehicle. However, the condenser head pressure increases due to high engine coolant temperatures, and that has a negative impact on vent outlet temperatures.

Inner Condensers. With the application of heat pump systems for electric vehicles, an inner condenser is required that provides heating for comfort and for defrosting. The inner condenser is placed within the HVAC unit (and thus the name as inner condenser) and is replaced by a heater core. During winter, the high pressure vapor from the compressor is fed into this inner condenser where the refrigerant vapor condenses, releasing the latent heat. This heat is picked up by the airstream flowing within the HVAC unit for comfort heating and for defrosting. Currently, dual zone inner condensers (Mathur 2022b) are being used in electric vehicles to provide heating to drivers and passengers.

Magnetic Cooling. Magnetic refrigeration is a promising alternative cooling technology (Monfared et al. 2014; Yanik and Celik 2018). When a suitable magnetic material is exposed to a changing magnetic field, it undergoes a temperature change (**magneto-calorific effect**). When the material is magnetized (i.e., an increase in the magnetic field), its temperature increases. When the material is demagnetized (i.e., decrease in the magnetic field), its temperature decreases. The cooling intensity depends on the magnetic material used. Magnetic refrigeration essentially works by recapturing produced cooling energy via a heat transfer fluid, such as water. Magnetic cooling is quieter, safer, more compact, higher efficiency, and environmentally friendly (as no refrigerants are used for cooling). In MACS applications, approximately 682 Btu/h (at a Δt of 36°F; Torregrosa-Jaime et al. 2013) of cooling has been achieved with the currently available magnetic materials. A lot of research and development is being done in national laboratories, universities, and suppliers (within the United States and around the world) to develop new materials for magnets. The new material properties will result in improvement of cooling and heating power densities with relatively small magnets.

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 and Farkh 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 on 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.

Autonomous Vehicles. Autonomous vehicles (SAE *Standard* J3016) are self-driving, driverless, or robotic vehicles. A number of companies are working on such vehicles. Some of the proposed architecture, such as the front two seats turning 180° to face the rear occupants, is drastically different from traditional designs. These vehicles will have significant computing power (equivalent to that of about five to ten laptops) to process the data on a real-time basis. Expectations are that people will spend more time in autonomous vehicles, and that vehicle travel by nondrivers (e.g., older people who cannot drive anymore) will increase. One prediction is that a fleet of autonomous vehicles will be maintained by various companies and shared by the users, with reduced vehicle ownership. Advocates predict that by 2030 (Litman 2018), such vehicles will be sufficiently convenient and affordable to displace most human-operated vehicles, reduce driving stress, provide independent mobility to nondrivers, and be a panacea for congestion, accident, and pollution problems. The architecture of the HVAC system will be very different for autonomous vehicles. Additional heat generated by the computers will have to be removed by the HVAC system or using an independent cooling system. There is a strong need to develop extensive control strategies for heating, humidification, dehumidification, and cooling for these vehicles.

High Voltage Water Heaters

Currently hybrid and electric vehicles require high voltage water heaters to condition the battery and comfort heating. Electric vehicle manufacturers are looking into heaters that can deliver from 3 to 10kW of heat. A few electric vehicle OEMs are designing their heat pump systems with two independent high voltage water heaters – one for battery heating and the second one for comfort heating and or defrosting. The controls for using two independent high voltage water heaters (e.g., 3 kW and 7 kW) in a vehicle are less complex in comparison to using a single high capacity (10 kW) high voltage water heater. Currently high voltage water heaters are available in 3 to 10kW range operating at 450V. High voltage 800+V systems are being developed to enable faster battery charging. Safety requirement is a key element in the design of high voltage water heaters. Construction of these water heaters can be with heating elements or with PTC heaters. Figure 19 shows a typical high voltage water heater.

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