Energy Efficiency (2015) 8:1201–1229
DOI 10.1007/s12053-015-9389-4

REVIEW ARTICLE

Achieving a better energy-efficient automotive air-conditioning system: a review of potential technologies and strategies for vapor compression refrigeration cycle

M. F. Sukri · M. N. Musa · M. Y. Senawi · H. Nasution

Received: 23 September 2014 / Accepted: 17 August 2015 / Published online: 26 August 2015

Abstract This article presents a review of potential technologies and strategies to develop an energy-efficient automotive air-conditioner based on the vapor-compression refrigeration cycle system. This paper is broadly divided into two sections. The first is a review of component optimization (primary and secondary components) that enhances the energy efficiency of the automotive air-conditioning (AAC) system. The second presents a review of operational management and control that efficiently consumes energy in operating the AAC system while maintaining vehicular thermal comfort satisfaction. Some of the technologies and strategies described in this article are still conceptual and are the subject of ongoing research. However, the growing demand to reduce energy consumption by developing a new AAC system has led to an increasing number of related studies aimed at generating alternative conventional systems in the near future.

Keywords Automotive air-conditioning system · Efficient component · Energy efficiency improvement · Operational management

Nomenclature

A/C	Air-conditioning
AAC	Automotive air-conditioning
CRC	Conventional refrigerant cycle
DEAC	Dual-evaporator air-conditioning
DX	Direct expansion
EEV	Electronic expansion valve
EV	Electric vehicle
EVDC	Externally controlled variable capacity compressor
FCC	Fixed capacity compressor
FDC	Fixed displacement compressor
FSTPID	Fuzzy self-tuning proportional integral derivative
HVAC	Heating, ventilation, and air conditioning
MEC	Modified ejector cycle
RV	Revolving vane
SC	Standard cycle
SEC	Standard ejector cycle
TEV	Thermostatic expansion valve
TPERC	Two-phase ejector refrigerant cycle
VAV	Variable air volume
VCC	Variable capacity compressor
VCR	Vapor compression refrigeration

M. F. Sukri · M. Y. Senawi
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

M. F. Sukri (✉)
Efficient Energy and Thermal Management Research Group, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
e-mail: mohdfirdaus@utem.edu.my

M. N. Musa
UTM-Ocean Thermal Energy Center (UTM-OTEC), Universiti Teknologi Malaysia Malaysia, Jalan Semarak, 54100 Kuala Lumpur, Wilayah Persekutuan Kuala Lumpur, Malaysia

H. Nasution
Automotive Development Centre, Universiti Teknologi Malaysia Malaysia, 81310 Johor Bahru, Johor, Malaysia

VCRAAC	Vapor compression refrigerant, automotive air-conditioning
2LP	Secondary loop system
h	Refrigerant enthalpy, kJ/kg
p	Pressure, bar
T	Temperature, °C
V	Air velocity, m/s

Subscripts

ai	Air inlet
comp	Compressor
cond	Condenser
evap	Evaporator
FCC	Fixed capacity compressor
m	Mean
VCC	Variable capacity compressor

Introduction

Transportation is a key component of economic development and human welfare, and this technology continues to expand around the world as economies grow (Kahn Ribeiro et al. 2007). Sand and Fischer (1997) showed that an automobile runs for an average of 249 h annually, and using an air-conditioning (A/C) system was estimated to account for 107 to 121 h per year (Fischer 1995) or 43–49 % of the vehicle usage. The actual use of the A/C system varies considerably depending on factors such as climate, time of day, season, vehicle type, vehicle color, outdoor/indoor parking, clothing of occupants, activity levels of occupants, length of trip, vehicle speed, and personal preference (Farrington and Rugh 2000); thus, the usage is expected to be higher than reported in hot and humid countries.

Johnson (2002) showed that A/C vehicles in the USA use 27 billion liters of gasoline annually, which is equivalent to 6 % of the domestic petroleum consumption or 10 % of imported crude oil. Alahmer et al. (2012) stated that the A/C system accounts for 30 % of mile-per-gallon expenditure. Comfort is not the only reason for using automotive air-conditioning (AAC) systems; road safety also improves with the comfort of the driver and a pleasant environment reduces driver fatigue (Konz 2007). The A/C system consumes a relatively high amount of energy, which becomes a disadvantage, particularly for full electric vehicles (EVs), because of the limited battery storage capacity of such vehicles. The battery is used not only to operate the electric motor of EVs but also to power the A/C system and other accessories, thereby reducing the driving range of EVs. One way to reduce the effect of various types of energy usage on the general performance of the vehicle is to increase the efficiency of the AAC system by adopting innovative technologies and strategies.

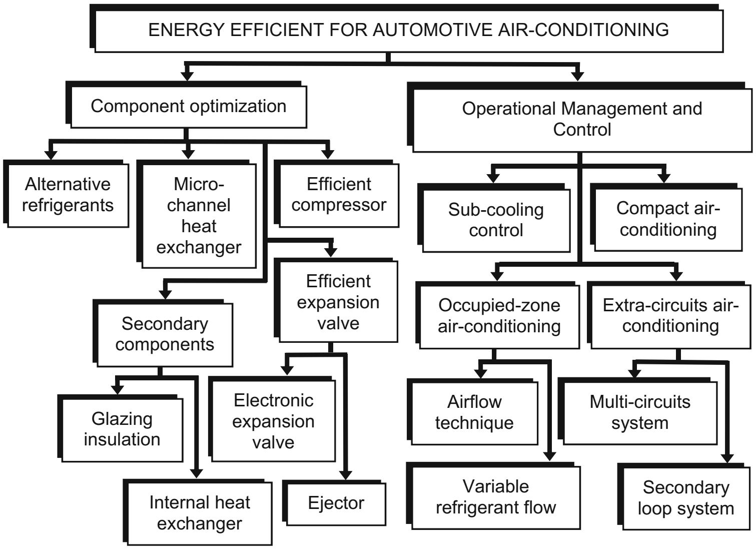
In general, a more efficient AAC system can reduce energy consumption, thereby decreasing greenhouse gas emissions. This low-carbon technology is highly relevant in the real world and an important research subject in energy-efficient systems. Many countries, particularly developed ones, have policies to reduce greenhouse gas emissions at the residential level, as well as in the manufacturing and transportation industries. Numerous studies have been conducted on A/C and heat pumps (Li et al. 2014a; Li 2015).

Therefore, the present study aims to review the literature on energy efficiency and the A/C system, particularly on technologies and strategies for the vapor compression refrigeration (VCR) and the AAC system. The review begins by documenting the effect of demand for an energy-efficient AAC system. As shown in Fig. 1, this review is divided into two key categories that are organized systematically. The system components that enhance the energy efficiency of the A/C system are reviewed, followed by operational management and control design strategies that possibly reduce the energy use of an A/C system.

Impact on demand of energy-efficient AAC system

A typical AAC system for internal combustion engine-powered vehicles is based on a fixed displacement compressor (FDC) that continuously runs at maximum capacity (i.e., conventional bus A/C system) (Mansour et al. 2008) or works on and off to meet the A/C demand (i.e., AAC system) (Tian et al. 2005). This system creates thermodynamic losses, disturbance to the engine (Tian et al. 2005), and human thermal discomfort particularly with low cooling loads, which eventually lead to inefficient energy usage (Mansour et al. 2008). In hot and humid countries, the AAC system is crucial in providing vehicular thermal comfort. The A/C system is the second largest consumer of energy after the power train (Roscher et al. 2012), which becomes a critical

Fig. 1 A generalized outline of the technical review for energy efficiency in automotive air-conditioning



issue in the development of new vehicles because of increasing concerns regarding energy cost, thermal comfort, greenhouse gas emissions, and vehicle range (particularly for full EVs). The demand for an energy-efficient AAC system is a priority in the manufacturing of new vehicles, and this system can be an important innovation in future vehicles.

Figure 2 shows the effect of the heating, ventilation, and air-conditioning (HVAC) system on the cruising range of the EVs. The cruising range is critical for EVs because of its limited battery storage capacity and battery charging station, as well as its longer charging time compared with conventional internal combustion engine-powered vehicles. Farrington and Rugh (2000) showed that an increase of the accessory load from 500 to 3500 W would cause the EV range to decrease by 7 to 38 %. According to Kwon et al. (2012a), the EV driving range is approximately 140–160 km on a single charge; however, if the HVAC is turned on, this range is reduced by 20 to 30 %. Chen et al. (2011) observed that the total mileage of an EV decreases by 50 % when the A/C is on, making the vehicle impractical for city transportation. AAC cooling loads are the most significant auxiliary loads (Zhang et al. 2009; Kaushik et al. 2011), so the AAC system has to consume energy efficiently to minimize the reduction in the cruising range when the AAC system is turned on.

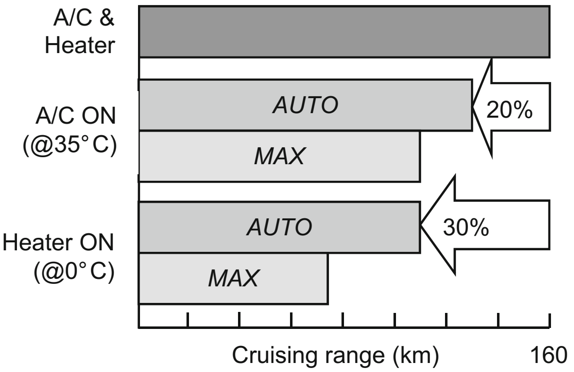


Fig. 2 Effect of HVAC system on the cruising range of EVs (Umezu 2010)

Future vehicles such as EVs must meet the needs of consumers in city driving and traveling longer distances for holiday outings. One essential element is the vehicular thermal comfort provided by the A/C system that runs on batteries. The AAC system is a standard accessory, but it reduces the driving range in an EV after every battery-charging cycle. In addition to the limited battery-storage capacity, an energy-efficient EV A/C system is important to achieve both vehicular thermal comfort in the vehicle and extend the range as far as possible.

An energy-efficient AAC system can reduce the energy consumption and improve the overall performance of the vehicle. As a result, it also helps reduce the greenhouse gas emissions of internal combustion engine-powered vehicles. Therefore, an energy-efficient AAC system not only improves vehicle performance but also, and more importantly, helps protect the environment for future generations.

Component optimization

A typical automotive A/C has four primary components: compressor, condenser, expansion valve, and evaporator. Previous studies showed that component optimization is a potential technique to achieve an energy-efficient A/C system. In the open literature, energy-efficient components, including compressors, micro-channel heat exchangers, ejectors, and electronic expansion valves, are recognized as the key components in developing an energy-efficient AAC system. Environment-friendly alternative refrigerants with the potential to improve the system performance compared with the HFC-134a used in the current AAC system are also considered. Secondary components of advanced glazing and insulation as well as internal heat exchangers (IHX) are also identified as possible options in developing an energy-efficient AAC system.

Efficient compressor

The compressor, the most important component of the A/C, serves as the heart of the system; thus, power is necessary to operate the AAC compressor (Farrington and Rugh 2000). According to Park et al. (2006), the compressor consumes the highest amount of energy (65 %) in a typical vapor compression refrigeration, automotive air-conditioning (VCRAAC) system. Therefore, a small improvement in compressor efficiency leads to a larger reduction in power consumption. Considerable efforts have been exerted to improve energy efficiency in cases where a substantial amount of energy is consumed. In general, scientific articles in the literature related to efficient compressor A/C systems discuss an existing well-proven compressor or newly developed experimental compressor.

Existing well-proven compressor

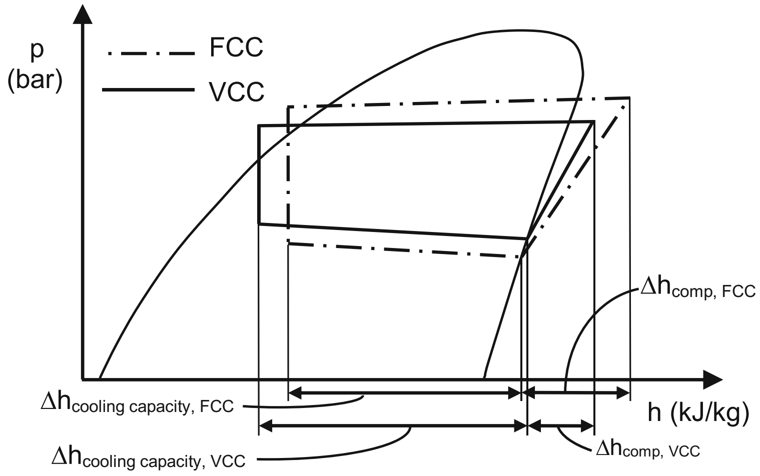
Research on the variable capacity compressor (VCC) in an AAC system using HFC-134a was first reported by Dieckmann and Mallory (1992) for EVs because of the urgent need to produce energy-efficient vehicles. As shown in Fig. 3, compared with the fixed capacity compressor (FCC), the VCC produces a higher cooling capacity at lower compressor energy consumption. Park et al. (2006) studied the variable displacement swash-plate compressor in an AAC system and found that this compressor could improve the fuel consumption ratio by 6.1–8.6 % compared with a fixed swash-plate compressor.

Qi et al. (2007) analyzed the performance of an AAC system with an externally controlled variable capacity compressor (EVDC). The capacity control method is based on the evaporator surface temperature and cabin temperature. As shown in Fig. 4, Qi et al. (2007) found that during the entire test period, the cabin temperature in an EVDC system remained the same for 24 min even if the Sun load changed after the experimental investigation. By contrast, the cabin temperature in a FDC system significantly decreased to approximately 20 to 21 °C when the Sun load changed down-up. Eventually, the FDC system performed poorly because it was unable to reach the required cabin temperature of 25 °C after 45 min. These findings indicate that the FDC system causes thermal discomfort and consumes more energy.

Alkan and Hosoz (2010) also conducted an off-road experimental study on the performance of an AAC system using FCC and VCC under steady-state conditions. The VCC operations are equipped with a capacity control system. As shown in Fig. 5, the coefficient of performance (COP) in the VCC operations minimally decreased and became almost constant after a certain compressor speed because of the intervention of the capacity control system. As a result, the VCC operations yielded a higher COP in the operations at a high compressor speed compared with the FCC operations. However, at $T_{\mathrm{cond,ai}} = 40$ °C and $T_{\mathrm{evap,ai}} = 40$ °C, the VCC operations produced continually diminishing COPs because of the limitations in operating the capacity control system. In general, VCC operations with an appropriate capacity control system can adapt to meet the required cooling capacity while constantly operating in a wide range of compressor speeds, in contrast to the on/off operation of FCC. As shown in Fig. 6, the rate of total exergy destruction in the VCC operations remain almost constant after a certain compressor speed, but gradually increases with the compressor speed in the FCC operations. The ability to maintain a higher COP and reduce exergy destruction in the circuit with a wide range of compressor speeds indicated that VCC operations are more efficient than FCC operations.

The VCC/EVDC system with its appropriate capacity control system can accurately change the compressor capacity according to the changes of the ambient conditions. This ability successfully provides better thermal comfort to the passenger and saves more energy compared with the FCC/FDC system.

Fig. 3 Image of cycle efficiency improvement (Park et al. 2006)



Experimental compressor

Teh and Ooi (2009d) stressed that an energy-efficient compressor could be achieved in two ways: by improving the existing compressor design or by introducing new designs that are expected to overcome the limits of the existing compressor. The new rotary compressor design optimization with a combination of geometrical dimensions and minimum mechanical losses at given operational conditions and swept volume (Ooi 2005) theoretically reduces mechanical losses by approximately 50 % and improves the COP of the compressor by more than 14 %. Also, a new gas compression mechanism called the “revolving vane” (RV) compressor was invented and theoretically shown to achieve improved mechanical, volumetric, and compression efficiencies compared with other existing compressor designs. This new compressor design uses the radial concept of a rotating cylinder to effectively reduce frictional losses. The schematic of the RV compressor is shown in Fig. 7. Theoretical studies have shown that friction, leakage, and discharge loss were substantially reduced in the new design, leading to significant improvements in efficiencies (Teh and Ooi 2009a; Teh and Ooi 2009b; Teh and Ooi 2009c). Figure 8 shows snapshots of the RV compressor operation.

An experimental study at a shaft speed of 600–1200 rpm (Ooi 2005) on the prototype of a RV compressor with air as the working fluid proved the reliability of the mechanism, achieving pressure ratios higher than 8:1 and more than 30 h of operation without any failure. Later, the design improvements by Tan and Ooi

Fig. 4 Comparison of in-car temperature between EVDC and FDC system at desired passenger compartment and ambient temperatures of 25 and 35 °C (Qi et al. 2007)

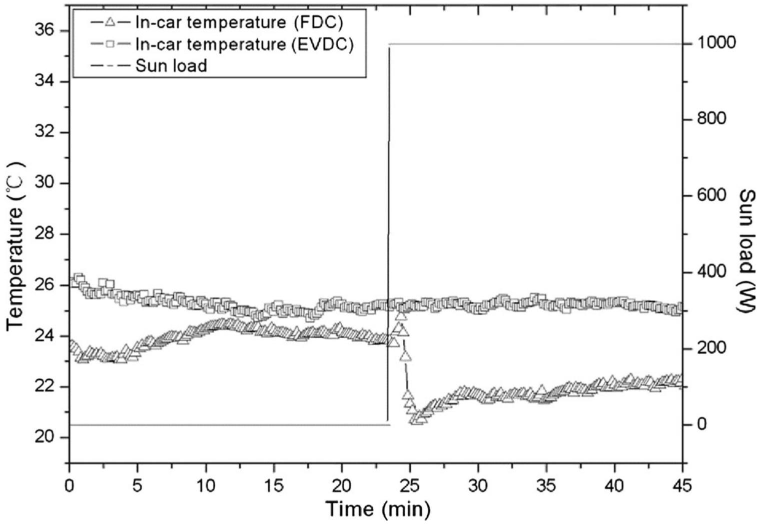
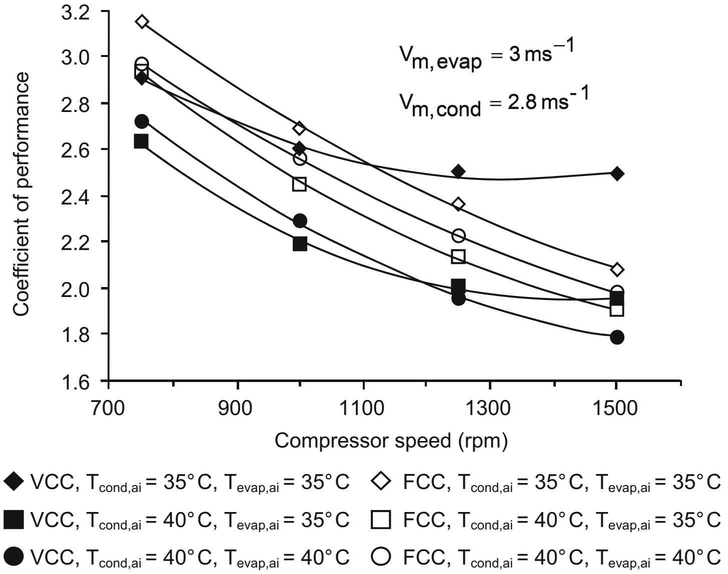


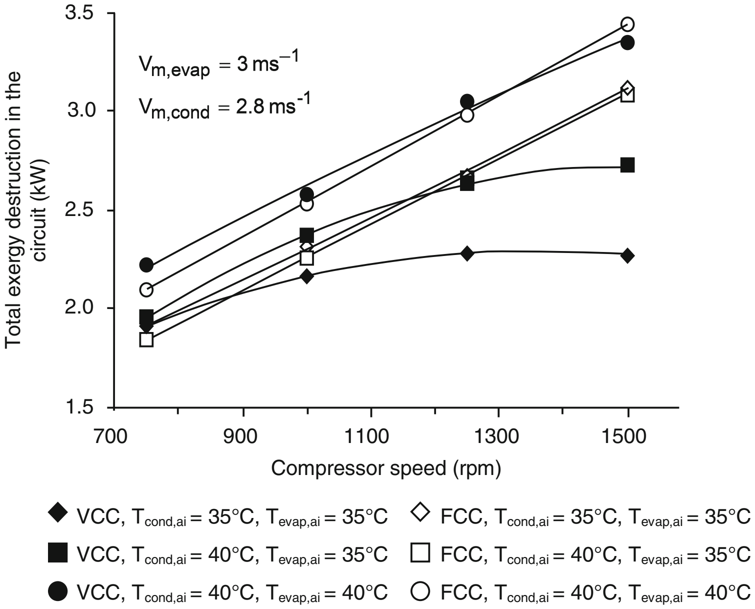
Fig. 5 Variations in the coefficient of performance with the compressor speed (Alkan and Hosoz 2010)



(2011) of the RV compressor with a fixed-vane significantly reduced the frictional losses by 18 to 41 % and mechanical efficiency by 96 % compared with the older RV compressor design.

In recent years, interest in using the electric compressor to replace the current compressor has grown. By utilizing this compressor, any problem related to the interaction of the refrigerant cycle components and the rapidly changing operating conditions of the vehicle (speed, revolutions per minute, and so on) is solved. Murakami et al. (2001) introduced a method of designing an interior permanent magnet synchronous motor (IPMSM) for a 42-V ACC with an efficiency of 94 % at 15,000 rpm. The technology used by this highly efficient and super-fast motor is extremely different from mainstream technologies. The successful application of this motor with a suitable compressor in the automotive industry can lead to the improved efficiency of the AAC system and the overall efficiency of the vehicle itself. However, according to the author's knowledge, no

Fig. 6 Variations in the total exergy destruction in the refrigeration circuit with the compressor speed (Alkan and Hosoz 2010)



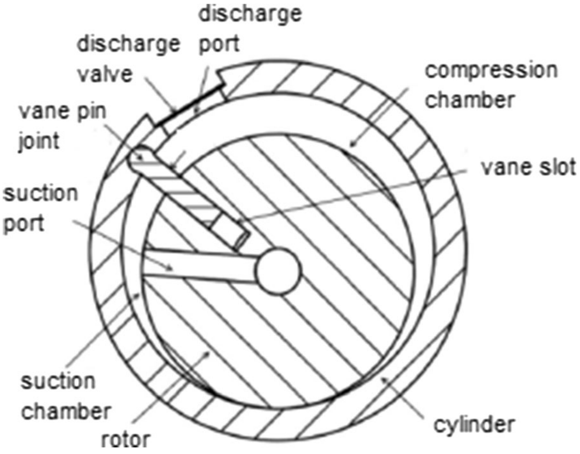


Fig. 7 Schematic of the RV compressor (Tan and Ooi 2011)

study has analyzed this highly efficient, super-fast motor in combination with a suitable compressor.

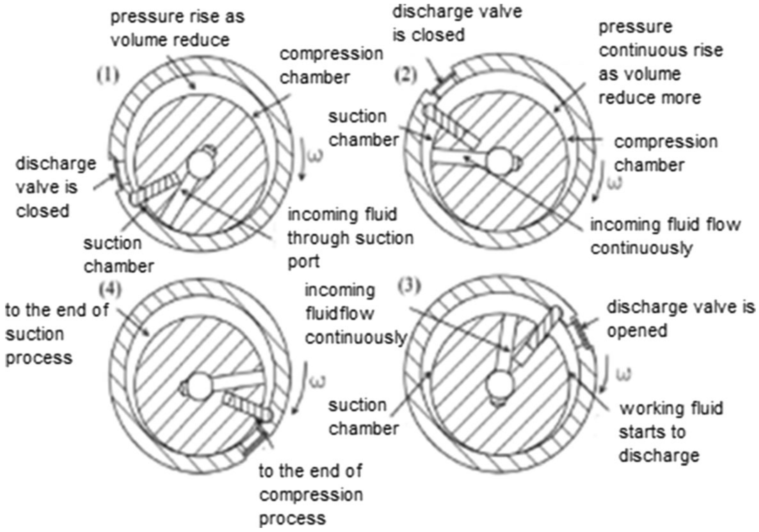
Ekren et al. (2013) demonstrated that direct current compressors have the potential to be used in energy-efficient refrigeration systems because these compressors do not require additional components such as a power inverter that an alternative current compressor would require. All types of ground vehicles are equipped with direct current batteries; thus, the authors agreed that efficient direct current compressors are also among the best options to be used in an energy-efficient AAC system. Nevertheless, further investigations such as the stability of the batteries to consistently supply energy to the compressor for a longer time are required to justify the advantage of this compressor in developing an AAC system in the future.

Micro-channel heat exchangers

Micro-channel or compact heat exchangers are widely used in modern A/Cs, heat pumps, and refrigeration systems for residential, industrial, automotive, and process industry applications because of their potential to enhance the heat transfer coefficient (Kim et al. 2003; Han et al. 2012). These types of heat exchangers have advantages in compactness (17.2 and 15.1 % volume reduction for the evaporator and condenser, respectively), weight (2.8 and 14.9 % lighter for the evaporator and condenser, respectively), and heat transfer characteristics compared with the currently used heat exchangers in the AAC industry (Qi et al. 2010). Han et al. (2012) highlighted that the reduced scale leads to enhanced fluid compressibility effects, and increased roughness leads to increased drag coefficient; the increased surface area-to-volume ratio strengthened the effects of the force associated with the area (surface forces, viscous forces, and so on) and enhanced the effects of the axial heat conduction of the micro-channel wall.

Park and Hrnjak (2008) analyzed the effect of the different types of condensers on the performance of R410A residential A/C systems and showed that both the COP and cooling capacity of the system with the micro-channel condenser were higher than those of the round-tube condenser in all test conditions. The performance enhancement study by Qi et al. (2010) on the AAC system indicated that the enhanced system with more compact heat exchangers could reduce the system charge, minimize the effective charge amount, and

Fig. 8 Snapshots of revolving vane compressor operation (Tan and Ooi 2011)



supply more cooling capacity to the car compartments under all test conditions because of the better performance of the heat exchangers than that of the baseline system. As a result, the cooling capacity and COP increased by approximately 5 and 8 % under a high vehicle speed, respectively (Qi et al. 2010).

Ribeiro et al. (2012) investigated the thermal-hydraulic performance of a micro-channel condenser with open-cell metal forms to enhance the air-side heat transfer. The researchers observed that, for a fixed pumping power, the overall thermal conductance of the metal foam condenser was lower than that of a plain fin condenser with similar characteristics. The effectiveness study by Yu et al. (2013) on anisotropic, micro-patterned aluminum fins plain fin-and-tube heat exchanger showed an enhancement in the performance through the reduction in the wet air-side pressure drop from 9.3 to 53 % and the negligible effect on the sensible heat transfer coefficient under dry and wet conditions.

Decrease in size and weight directly reduces the need for raw materials, lowering the cost of heat exchangers. Although the reduction in material is relatively small, it reduces the total weight and fuel/energy consumption of the vehicle. In addition, with better performance and efficiency, the micro-channel heat exchanger is among the best options for energy-efficient AAC systems. However, Han et al. (2012) concluded that the pressure loss and heat transfer characteristics in the proposed system must be accurately predicted before designing the micro-channel heat exchanger because the theoretical basis that can accurately guide the design has not been developed and no standard in manufacturing exists.

Efficient expansion valve

The expansion valve is used to reduce the pressure in a typical VCR system. It also regulates the flow rate of the refrigerant and controls the refrigerant to the evaporator suction pressure level (Huang 1998; Kaynakli and Horuz 2003). Typically, two types of conventional expansion valves are used in the A/C system: capillary tube and thermostatic expansion valve (TEV). However, few studies on creating a new type of expansion valve that enhances the overall system performance have been conducted and reported because of various concerns and market pressure in developing an energy-efficient A/C system.

Recently, the ejector has been intensively investigated as an expansion valve because it can control pressure and help reduce the power consumption of the compressor at the same time (Disawas and Wongwises 2004; Sumeru et al. 2012; Yan et al. 2013). The electronic expansion valve (EEV) also gained much attention because of its faster, accurate, and high-precision response to the variable load with a widely regulated range, thereby exhibiting the potential to improve the control quality and energy-saving capabilities of refrigeration systems compared with TEV (Li et al. 2004; Lui et al. 2007; Wang et al. 2010b).

Ejector as an expansion device

Ejectors improve refrigeration cycle performance because of their ability to reduce throttling losses and increase the efficiency of stationary and AAC systems (Sumeru et al. 2012, 2014). Three applications of an ejector on the VCR cycle were highlighted by Sumeru et al. (2012): ejector on the heat-driven refrigeration, ejector on the condenser, and ejector as an expansion valve. As shown in Fig. 9, two types of ejectors used as an expansion valve are reported in the literature, namely, standard ejector cycle (SEC) and modified ejector cycle (MEC). Lawrence and Elbel (2014) highlighted two types of SECs known as the single evaporation temperature, as shown in Fig. 9b, and two evaporation temperatures (Fig. 10).

As shown in the p-h diagram of Fig. 9a, the actual throttling process in the conventional expansion valve (from P2 to P11) produces an isenthalpic (constant enthalpy) process. This process increases entropy and energy loss in the throttling process. As a result, the evaporator cooling capacity decreased, which subsequently reduces the system performance. However, the ejector generates an isentropic (constant entropy) process (Sumeru et al. 2014) with no entropy generation. Thus, energy loss during the throttling process is reduced.

In addition, the compressor suction pressure (P1) of SEC (p-h diagram of Fig. 9b) is higher than the compressor suction pressure (P1) of the standard cycle without ejector (SC) (p-h diagram of Fig. 9a). SEC recovers expansion energy that was previously lost in the expansion valve, and converts it into pressure energy. The pressure lift provided by the ejector reduces workload by the compressor (process P1 to P2 in Fig. 9b), thereby reducing the overall power consumption and increasing

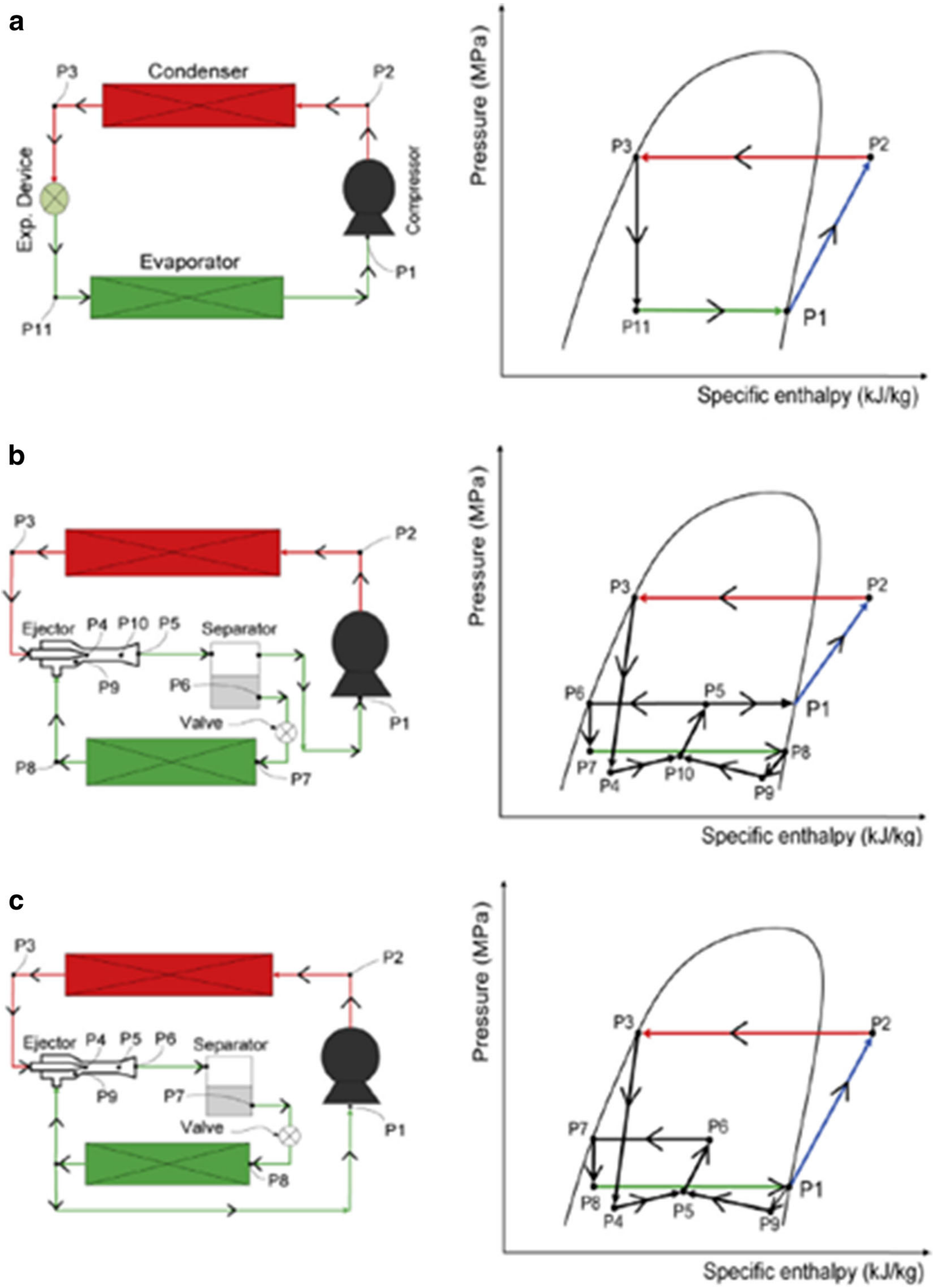


Fig. 9 Schematic and p-h diagram of the vapor compression refrigeration cycle. **a** Standard cycle. **b** Standard ejector cycle. **c** Modified ejector cycle (Sumeru et al. 2014)

the performance of the A/C system. According to Fig. 9, using the ejector also reduces the quality of the refrigerant entering the evaporator (P7 for SEC and P8 for MEC), thereby producing a higher cooling capacity

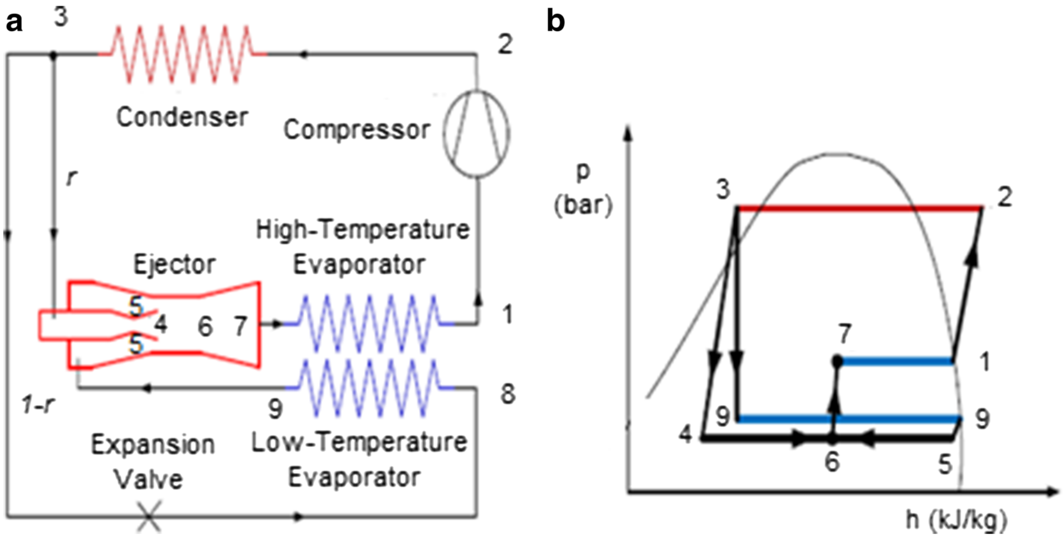


Fig. 10 **a** Layout diagram and **b** p-h diagram of SEC A/C system with two evaporation temperatures (Lawrence and Elbel 2014)

compared with SC. The reason is the overall heat transfer coefficient of the evaporator in the system with ejector is higher than that of the SC system under the same area of the evaporator.

These findings are consistent with experimental and numerical results published by other researchers. As shown in Fig. 11, at the same operating conditions, Lee at al. (2011) found that the system with the ejector caused the pressure in the compressor inlet (point 1′) to be higher than that (point 1) of a SC system. At the same time, the pressure in the compressor inlet of the SC system (point 1) and the pressure in the evaporator outlet of the system using an ejector (point 9′) are almost similar. The evaporating temperature and pressure in the compressor outlet (points 2 and 2′) of both systems are also similar. Consequently, the compressor work decreased by approximately 13 % and the COP of the system using an ejector is approximately 15 % higher than that of the SC system (Lee at al. 2011).

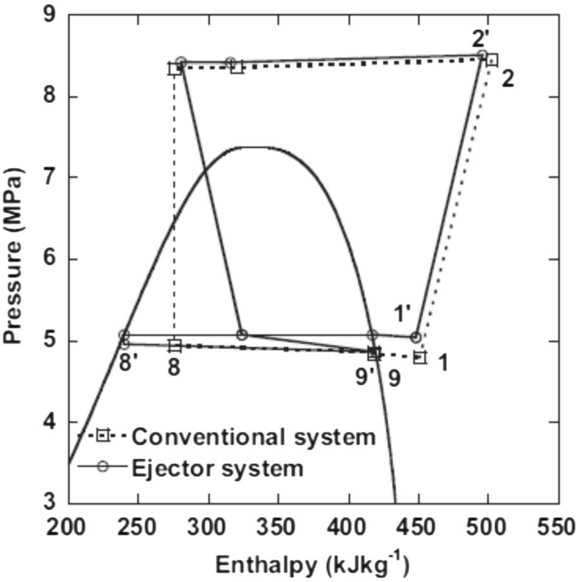


Fig. 11 p-h diagrams in CO_2 A/C system using and ejector and conventional/SC system (Lee at al. 2011)

Meanwhile, the higher cooling capacity with system using the ejector is also consistent with the experimental findings of Disawas and Wongwises (2004). The researchers determined that the cooling capacity in a system with a two-phase ejector refrigerant cycle (TPERC) is always higher than that of a conventional refrigerant cycle (CRC) in the same operating conditions (Fig. 12). As shown in Fig. 13, these observations cause the COP of the TPERC to be higher than that of the CRC in all experimental conditions.

Kairouani et al. (2009) showed that the COP of the conventional direct expansion (DX) multi-evaporator system utilizing the ejector is better, with an improvement of 15 %, than the same system without the ejector. Yan et al. (2013) determined that the COP of the combined ejector-vapor compression cycle based on R134a and air-cooled condenser improves by approximately 15.9–21.0 %. Studies on the performance of a CO_2 A/C system using the ejector as an expansion device by Lee et al. (2014) also indicated that the cooling capacity and COP in the A/C system using an ejector are higher than those in the conventional system at an

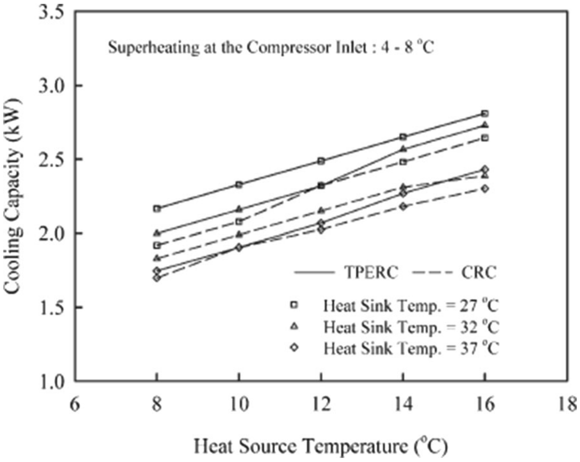


Fig. 12 Comparison of the cooling capacity between TPERC and CRC at various operating conditions (Disawas and Wongwises 2004)

entrainment ratio greater than 0.76. The entrainment ratio is the ratio of the mass flow rate in the suction nozzle to the motive nozzle of the ejector (Lee et al. 2014).

Sumeru et al. (2014) also conducted an experimental investigation on the effect of the ejector as an expansion valve to the performance of an A/C system. As shown in Fig. 14, the researchers found that at a constant ambient temperature, the MEC A/C system of a split-type air conditioner always consumed a lower compressor input power compared with a SC A/C system using the conventional expansion valve. Meanwhile, the reduction in compressor input power later improved the COP of the MEC by 13.78 %, as indicated in Fig. 15. The ejector and conventional expansion valve used in the experimental study was installed at the same experimental test rig to ensure that any change or improvement would not be attributed to other design changes.

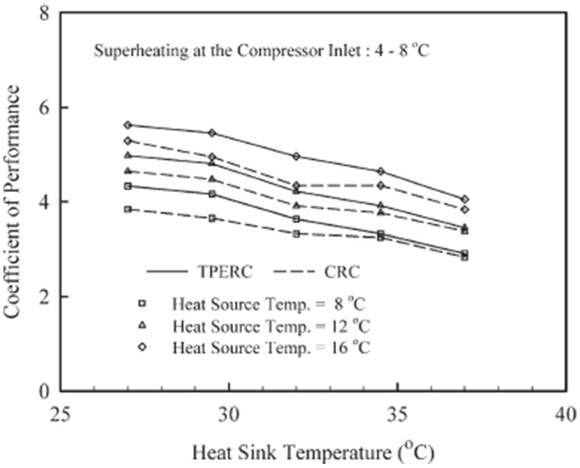


Fig. 13 Comparison of the cooling capacity between TPERC and CRC at various operating conditions (Disawas and Wongwises 2004)

All previous studies concluded that an ejector could replace the function of a conventional valve. The ejector increases the cooling capacity and reduces compressor work (at the same operating conditions) compared with the conventional expansion valve. Apart from having simple construction, high reliability, low installation, and low maintenance cost (Yan et al. 2013), the ejector is a potential replacement to the conventional expansion valve to increase the performance of the AAC system.

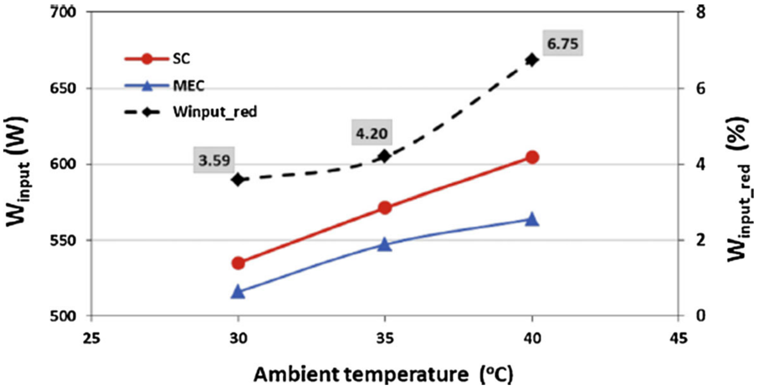
Electronic expansion valve

The cooling load in the passenger compartment varies with the daily conditions of the environment. Thus, an energy-efficient AAC system addresses this variation while saving energy. In this case, a throttling device can regulate the refrigerant mass flow rate to match the variable load. Thermal expansion valves (TEVs) have been widely used in the AAC system; however, in terms of energy efficiency, it has a slow response speed and low response precision to variable load. Mitsui (1987) studied the TEV based on the VCC system and demonstrated that the evaporator performance deteriorates at an initial stage because of the shortage of the refrigerant flow caused by the response delay of the TEV.

To improve the refrigerant flow control method, the concept of EEV-based AAC system was first proposed by Mitsui (1987) for a conventional on/off AAC system. Nowadays, the latest research on the A/C system also focuses on EEV as a replacement for the conventional expansion valve because of the quick response of the electrical signal. Wang et al. (2010) highlighted that, with the growing popularity of energy-efficient air conditioners, the application of EEV has widened and many studies on EEV have focused particularly on its flow characteristics.

Li et al. (2004) described the improvement of the refrigerant flow control method using an EEV driven by a stepper motor in the AAC system. Figure 16 shows the experimental results on the variations of the evaporator discharge air temperature over time for the AAC system using the fuzzy self-tuning proportional integral derivative (FSTPID) and conventional PID as a control system for EEV. The experimental study was conducted under the same operating conditions. Using FSTPID has

Fig. 14 Variation of input power (W_{input}) and input power reduction (W_{input_red}) with ambient temperatures (Sumeru et al. 2014)



lowered the evaporator discharge air temperature by approximately 3 °C compared with that of the conventional PID control system. This observation implies that the cooling capacity is increased at equal compressor workload, thereby improving the COP of the system. Therefore, the EEV with its appropriate control system can provide the adequate refrigerant flow into the evaporator in various operations and produce an energy-efficient system compared with the conventional AAC system.

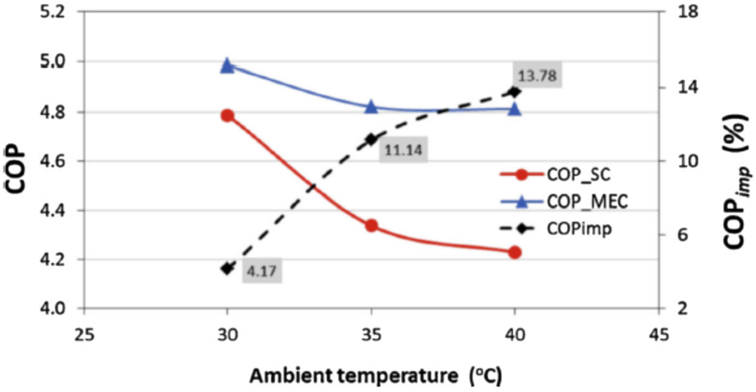
An efficient EEV is important for a VCR A/C system that works on the basis of variable refrigerant flow (VRF). This system produces the desired cooling capacity based on the imposed cooling load in the cabin compartment by controlling the refrigerant flow/volume in the refrigerant cycle using the EEV and VCC. By changing the refrigerant flow, the power consumption of the compressor is reduced, particularly at the lower cooling load, thereby saving energy while maintaining human thermal comfort. The potential of the VRF system for the AAC system is explained in the section of "Variable refrigerant flow air-conditioning system."

Alternative refrigerants

The refrigerant of HFC-134a has zero ozone-layer depletion potential (ODP = 0) but high global warming potential (GWP = 1340) (Wu et al. 2014; Li et al. 2014b). The HFC-134a in the current AAC system will eventually be phased out because of strong legislative pressure to protect the environment from global warming by reducing greenhouse gases. Li et al. (2014b) highlighted that legislation in the European community requires the use of refrigerants with a GWP that is less than 150 in all new vehicle types beginning in 2011 and in all new vehicles by 2017. Thus, the alternative refrigerant of R134a will be introduced to meet the dual environmental demands of the zero ODP and low GWP.

The type of refrigerant also influences the performance of the AAC system; thus, a few studies have reported the effect of alternative refrigerants on the performance of the AAC system as a replacement for HFC-134a (Steven Brown et al. 2002; Tamura et al. 2005; Wongwises et al. 2006; Cho et al. 2013; Han et al. 2013; Qi 2013;

Fig. 15 Variation of COP and COP improvement with ambient temperatures (Sumeru et al. 2014)



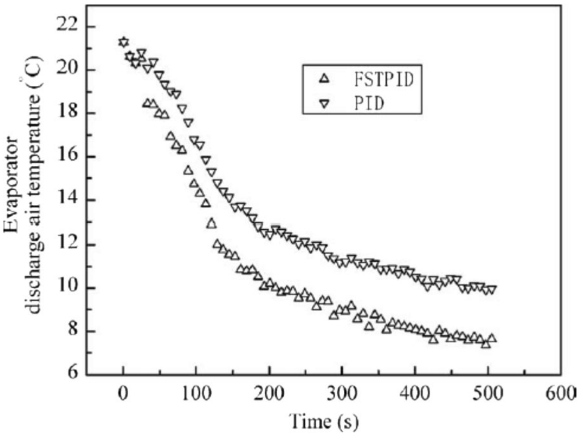


Fig. 16 Comparison of evaporator discharge air temperature for EEV using FSTPID and conventional PID (Li et al. 2004)

Wu et al. 2014; Li et al. 2014b). Table 1 shows the previously proposed alternative refrigerant and its effect on the performance of the AAC system. As shown in Table 1, the potential refrigerants replacing HFC-134a are CO_2, the mixture of HC-290/HC-600/HC-600a, HFO-1234yf, the mixture of HFC-161/HFC-134a, HFC-161, HC-290, HC-600a, and HFC-152a.

All those potential alternative refrigerants have a zero ODP and lower GWP that is less than 150 with better COP compared with a system with HFC-134a except CO_2, the mixture of HFC-161/HFC-134a (60 %/40 %), and HFC-1234yf. As a natural refrigerant, CO_2 is the best GWP, but it does not improve the system performance and it requires operation at high pressure, which results in energy and cost issues. The mixture of HFC-161/HFC-134a at 60 or 40 % possibly has a GWP higher than 150, whereas HFC-1234yf decreases the system performance compared with the HFC-134a system. Hydrocarbon (HC) refrigerants have low GWP value but are not popular because of safety concerns, such as flammability (Li et al. 2014b).

Table 1 indicates that the effect on COP depends on the thermophysical properties of the proposed refrigerants, which are suitable for the projected AAC system. An increase or decrease in cooling capacity and compressor power occurs because of energy balance. A dominant increase in cooling capacity, as opposed to a rise in compressor power, as well as a prominent decrease in compressor power, rather than a decline in cooling capacity, leads to the improvement of COP. Any possible alternative refrigerant, which has zero ODP and low GWP, minimal safety concerns, and adaptability with the current AAC system designed for HFC-134a with or without minor modifications, may replace HFC-134a in the near future. Evidently, the alternative refrigerant that performs at least equally as the system with R134a is preferred.

A limited number of refrigerants improve the COP and require specific modifications to the current DX AAC system. For example, flammable refrigerants, such as HC-290 and HFC-152a, require a secondary loop system to reduce their flammability risk. Therefore, further investigation is necessary to justify the best refrigerant before it can be commercially marketed for future AAC systems.

Secondary components

In addition to the main components, adding secondary components has a successful result in achieving an energy-efficient AAC system. Secondary components, such as an IHX, as well as advanced glazing and insulation materials, can be directly or indirectly installed to the AAC system to reduce its energy consumption.

Internal heat exchanger

An IHX functions as an efficient heat transfer device for energy or heat recovery (Abd El-Baky and Mohamed 2007; Ahmadzadehtalatapeh 2013). The IHX can be installed in the refrigerant pipeline at the location indicated in Fig. 17 to exchange energy between the warm liquid of the refrigerant exiting the condenser and the cool gas of the refrigerant leaving the evaporator. Therefore, the IHX affects the performance of the A/C system by influencing both its high and low pressure sides.

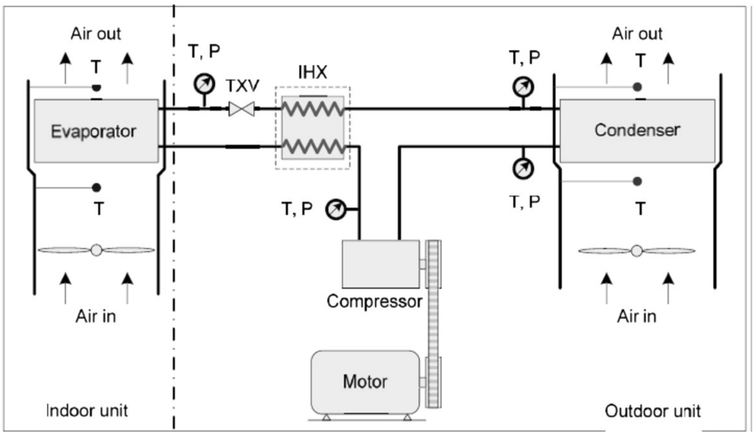
As shown in Fig. 18, the enthalpy of the refrigerant leaving the condenser (i.e., point 3) decreases before entering the expansion device (i.e., point 4) by rejecting energy to the vapor refrigerant leaving the evaporator (i.e., point 1) before entering the compressor (i.e., point 2). The cooling of the condensate that occurs on the high-pressure side (i.e., point 3 to point 4) increases the cooling capacity and reduces the probability of liquid flashing prior to reaching the expansion valve (Klein et al. 2000). In the low-pressure side, the IHX increases the temperature and reduces the pressure of the refrigerant entering the compressor, causing a decrease in the refrigerant density and compressor volumetric efficiency (Klein et al. 2000). Consequently, the refrigerant mass flow decreases as the effectiveness of the IHX increases. However, the refrigerant effect per unit mass

Table 1 Summary of previous studies related to performance of AAC system with alternative refrigerants

Authors	Alternative refrigerants	GWP	ODP	Performances
Steven Brown et al. (2002)	CO_2	1	0	• System with R134a has better COP where the COP of CO_2 system is lower by 21 and 34 % at $T_{ai,cond}$ of 32.2 and 48.9 °C, respectively.
Tamura et al. (2005)	CO_2	1	0	• Cooling COP ratio to HFC-134a AAC system is 1.00.
Wongwises et al. (2006)	mixture of HC-290/HC-600/HC-600a	20/20/20	0/0/0	• The mixture of HC-290/HC-600/HC-600a: 50 %/40 %/10 % yielded highest COP than HFC-134a in every tested condition.
Cho et al. (2013)	HFO-1234yf	4	0	Compared to AAC system with HFC-134a, system with HFO-1234yf has • Lower power consumption and cooling capacity up to 4 and 7 % respectively. • Cooling capacity and COP decreased up to 7 and 4.5 % (without IHX), and decreased by 1.8 and 2.9 % (with IHX), respectively.
Han et al. (2013)	Mixture of HFC-161/HFC-134a (60 %/40 %)	12/1340	0/0	Compared to AAC system with HFC-134a, system with proposed mixture refrigerant has • Higher COP of up to 8.4 %. • Higher cooling capacity and compressor power of about 32 and 30 %, respectively.
Qi (2013)	HFO-1234yf	4	0	• Cooling capacity of system with HFO-1234yf reduced up to 8.0 % in laminated type evaporator, but comparable and/or larger than that of HFC-134a up to 6.5 % in microchannel parallel flow evaporator.
Wu et al. (2014)	HFC-161	12	0	• The experimental COPs of system with HFC-161 were higher than those of HFC-134a at lower evaporation temperature but become closer at higher evaporation temperature. • The cooling capacities and compressor power of system with HFC-161 were about 56 and 47 % larger than those of system with HFC-134a, respectively.
Li et al. (2014b)	HFC-152a, HC-290	140, 3.3	0,0	Compared to direct expansion HFC-134a AAC system, at 35 °C of ambient temperature • COP of the HFC-152a secondary loop system (2LP) was increased by 5 and 10 % for highway driving and idling conditions, respectively. • COP of the HC-290 2LP was increased by 8 % and was decreased by 15 % under highway driving and idling conditions, respectively. • Total exergy destruction of the HFC-152a 2LP and HC-290 2LP was reduced around 9.6 and 14.3 % for highway driving conditions respectively. • A theoretical potential of COP and exergy destruction during idling condition for HC-290 2LP were approximately 15 % higher and 12.5 % lower than those of the HFC-134a system, respectively.

flow rate advances as a result of increased of enthalpy difference across the evaporator. Therefore, the beneficial effects of the IHX are offset by the refrigerant pressure drops that occur in it. Thus, the actual advantage of the IHX depends on its competing effect. In certain cases, the IHX improves the system performance, whereas it in other circumstances, it degrades the system performance.

Fig. 17 Schematic of experimental setup (Cho et al. 2013)



Klein et al. (2000) revealed the net effect of the IHX with mass flow rate correction and absence of pressure losses in the relative capacity index (RCI) for seven refrigerants as shown in Fig. 19. The RCI is defined as the value of cooling capacity with the IHX minus the cooling capacity without it, divided by the cooling capacity without the IHX at the same evaporating and condensing temperature. Few refrigerants have a higher RCI with an increased effectiveness of the IHX. One of the refrigerants is HFC-134a, which is widely used in the current AAC system. Furthermore, Klein et al. (2000) described in detail the method of obtaining the net result of the IHX on the COP with the effect of pressure loss. At this point, performing an economic assessment can determine the overall value of the IHX.

In general, an experimental investigation of IHX reported in the literature presented an improvement in the system COP. Desai et al. (2011) used the IHX for the AAC system. The experimental results indicated that the cooling capacity increases by 4.84 and 3.17 %, the COP increases by 11 and 7.18 %, and the compressor input power decreases by 6.05 and 4.18 % with the use of a copper and an aluminum IHX, respectively. A study by Cho et al. (2013) on the same AAC system experimental test rig demonstrated that a system with an IHX and HFO-1234yf can reduce the decrease in COP from 4.5 to 2.9 % compared with a system with an IHX and HFC-134a.

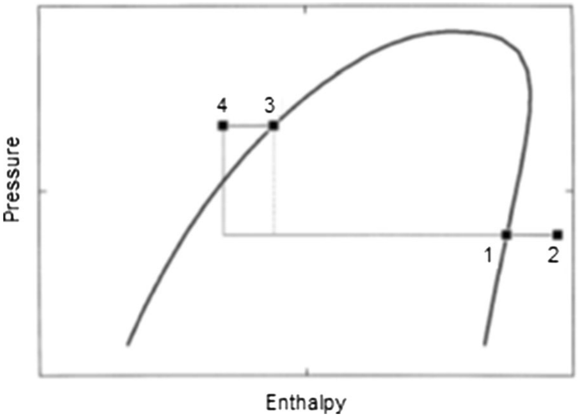


Fig. 18 p-h diagram indicating the effect of an idealized IHX (Klein et al. 2000)

Kwon et al. (2012a) analyzed the effects of sub-cooling heat exchanger (SCHX) on the performance of the multi-split VRF system. Results in the p-h diagram shown in Fig. 20 indicate that the multi-split VRF system with the SCHX performs more efficiently than the system without the SCHX. The advantages of the SCHX are due to the reduced pressure ratio, which leads to a reduction in power consumption, an improvement in compressor efficiency, and an increase in cooling capacity (Kwon et al. 2012a). Further details on the benefits of the sub-cooling control method are presented in the section of "Sub-cooling control."

Previous studies reveal that IHX is suitable for a system that uses HFC-134a or an alternative refrigerant of HFO-1234yf. Figure 19 proves the former where the relative system COP index increases with an IHX and becomes higher at a heightened heat exchanger effectiveness. The current AAC system utilizes HFC-134a; thus, an IHX may be suitable to increase the system performance. Furthermore, using an IHX reduces the possibility of liquid carry-over from the evaporator, which can damage the compressor (Klein et al. 2000).

In addition, COP calculation typically considers only the compressor work as input energy and the cooling capacity as output energy. However, certain secondary components, such as blowers, also consume a

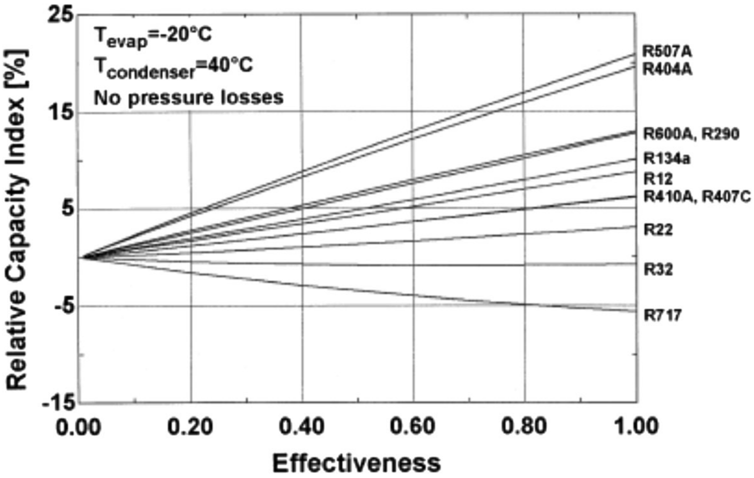


Fig. 19 Relative capacity (and relative system COP) index as a function of internal heat exchanger effectiveness for various refrigerants (Klein et al. 2000)

significant amount of input energy. If all of the input energy of each possible component is considered for a more realistic indication of the system COP, then the actual COP can be lower than expected. The use of an IHX becomes more advantageous in achieving an energy-efficient AAC system because the IHX does not require external power to operate. However, in certain cases, the IHX can decrease the performance of the A/C system; thus, further detailed analysis must be conducted, especially when a new type of refrigerant is used, to confirm the benefits of using an IHX before it can be implemented in an AAC system.

Advanced glazing and insulation materials

Vehicle heat gain or cooling load mainly comes from solar radiation through glazing surfaces. Sukri et al. (2012) emphasized that glass surfaces are recognized as the weak point of a building envelope in reducing building energy consumption. Their research on a commercial building indicated that 69.2 % of building heat gained is from solar heat gain through windows. Cordoba et al. (1998) noticed an approximately 12 % saving in building electricity consumption when a combination of solar control glass with thermal insulation was used. A similar problem is expected for vehicle cooling load because most of the exterior surfaces (i.e., front and rear windscreen and right and left windows) are made of glass.

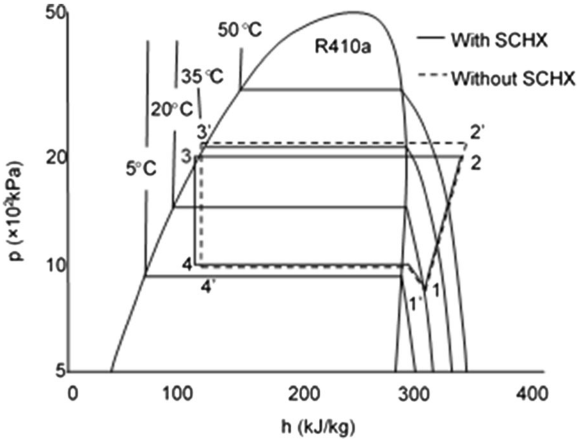


Fig. 20 Comparison of pressure and enthalpy diagram for refrigeration cycles with and without SCHX (Kwon et al. 2012a)

For vehicle application, a 50 % reduction in compressor power can be achieved by implementing vehicle insulation strategies in addition to “smarter” refrigerant components (Meyer et al. 2003). Fritsch (1991) concluded that double-glazing can improve passenger comfort while reducing the workload of an A/C system in a car. Farrington et al. (2000) demonstrated that glazing, which reflects the infrared portion of the solar spectrum, can reduce interior temperatures by 9 °C and reject more than 500 W while the vehicle is parked; thus, it improves the fuel economy of a compact car by approximately 0.3 km/l if the A/C system is appropriately downsized. Türler et al. (2003) stated that advanced insulation and window technologies reduce heating and cooling loads, which allows downsized HVAC equipment, increased fuel savings for conventional and hybrid vehicles, extended range for EVs, improved passenger comfort, reduced degradation of interior surfaces, and improved safety. Gasworth and Tankala (2011) illustrated that polycarbonate has lower thermal conductivity, which affords reduced steady-state heat transfer relative to glass and reduced nominal HVAC load in all of the operating conditions.

Thus, reduced vehicle solar heat gain through glazing surfaces (i.e., advanced glazing and insulation) can significantly lessen the cooling load as well as the energy consumption for a more energy-efficient AAC system.

Operational management and control

An energy-efficient AAC system can also be achieved through effective strategies in managing and controlling the system operation. According to the open literature, these strategies are sub-cooling control method, compact A/C system, extra-circuit A/C system, variable air volume, occupied-zone A/C system, and control of the refrigerant flow (i.e., VRF) in the A/C circuit.

Sub-cooling control

The COP and capacity of VCR cycles can be increased beyond what is possible through standard cycles by utilizing a dedicated sub-cooling control method (Thornton et al. 1994). Jensen and Skogestad (2007) highlighted that if allowed by design, sub-cooling can be used to increase the performance of the VCR cycle. Two potentially optimal designs with sub-cooling and no super-heating are shown in Fig. 21. According to Jensen and Skogestad (2007), these designs can be maximized only if the optimal value of sub-cooling and super-heating are used. Yang and Yeh (2015) supported this claim when they discovered that the optimal degrees of sub-cooling occur between 2 and 6 °C for initial cost saving and from 4 to 7 °C for total exergy destruction for R134a, R22, R410A, and R717.

Super-heating is unnecessary for optimal design (Jensen and Skogestad 2007) except to prevent the liquid refrigerant from entering the compressor. Therefore, a low-pressure tank (i.e., receiver drier) is installed after the evaporator as shown in Fig. 21, to allow only saturated vapor out of the evaporator at a steady state for optimum condition. Then, only two-phase flow occurs inside the evaporator tube, producing a better difference in temperature between cold two-phase flow refrigerant and the hot air. The heat transfer process increases between the two-phase flow refrigerant and the hot air. As shown in Fig. 21a, the expansion valve controls the degree of sub-cooling. Jensen and Skogestad (2007) mentioned two other options of sub-cooling control methods, namely, keeping the valve opening position at its optimal value and controlling the pressure. However, they emphasized that controlling the degree of sub-cooling produces a good self-optimizing control method.

Few studies related to the sub-cooling control method on the VCR cycle successfully increase the performance of the system. The case study by Jensen and Skogestad (2007) on an ammonia refrigeration unit revealed that sub-cooling in the condenser may result in 2 % savings in compressor power. Pottker and Hrnjak (2015) conducted an experimental study on the effect of sub-cooling on the performance of the A/C system operating with R134a and R1234yf under the same working conditions. As shown in Fig. 22, at a certain value of sub-cooling, the COPs of both refrigerants undergo a maximum effect because of

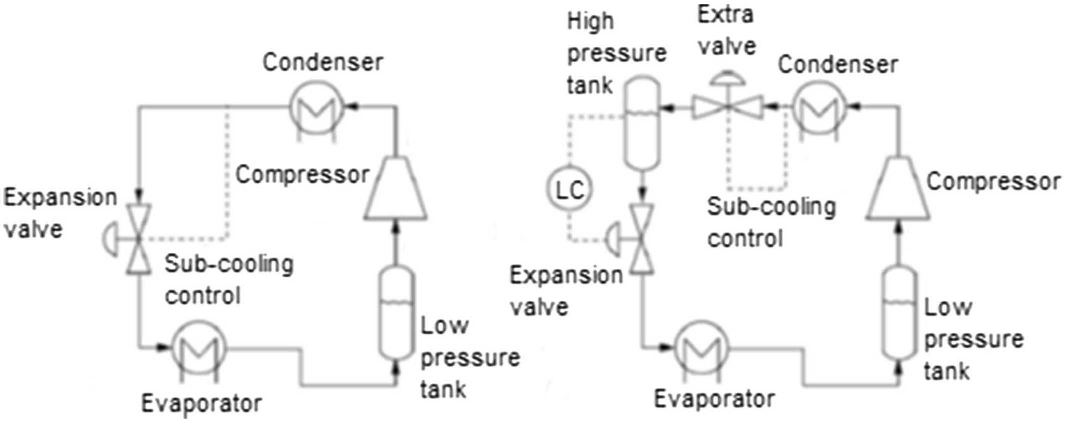
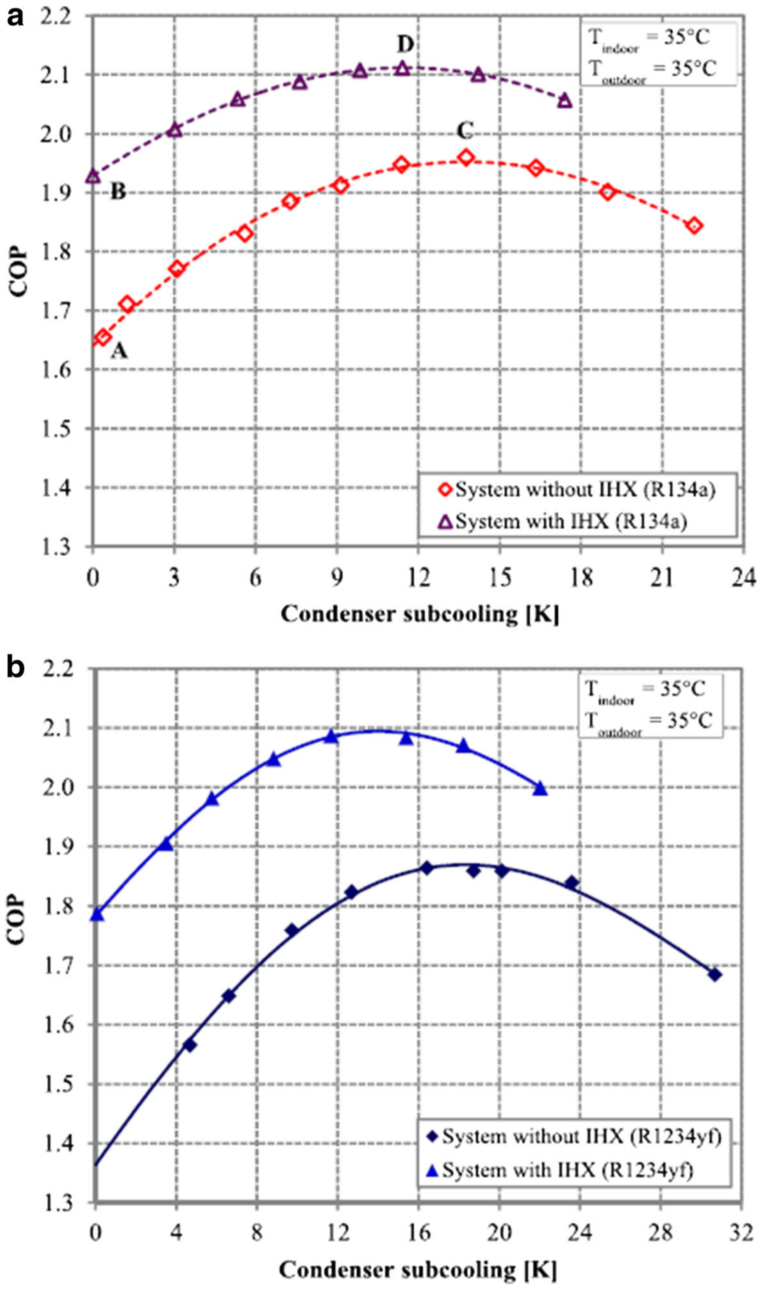


Fig. 21 Two potentially optimal designs with sub-cooling and no super-heating. **a** Optimal with one tank. **b** Optimal with two tanks. (Jensen and Skogestad 2007)

Fig. 22 COP as a function of the condenser sub-cooling for systems with and without IHX. **a** R134a. **b** R1234yf (Pottker and Hrnjak 2015)



the reduction of the condenser exit temperature and increase in specific compression work caused by an inflation in the condensing pressure. The maximum COP improvement for system using R134a because of condenser sub-cooling is 18 % (without an IHX) and 9 % (with an IHX). Moreover, using both (IHX and condenser sub-cooling) simultaneously yields a more efficient improvement of A/C system, especially for R1234yf.

Thus, standard VCR with sub-cooling cycle provides a lower heat sink temperature, resulting in a gain in capacity and COP, particularly at high ambient and low evaporator temperatures. In addition, sub-cooling allows the refrigerant to enter the inlet evaporator with a lower quality compared with a typical VCR cycle. The lower quality of the evaporator inlet produces an increase in the refrigeration capacity per unit mass of refrigerant circulated. However, induced by energy balance (neglecting losses to the environment), the increase in refrigeration capacity provided by sub-cooling must be equal to the heat addition to the system. This heat addition must be rejected through the condenser at the cost of extra compressor work as illustrated in Fig. 23. Therefore, a trade-off exists between the amount of extra refrigeration capacity provided to the system and the amount of work performed by the compressor. Jensen and Skogestad (2007) justified that a small degree of sub-cooling may be optimal to ensure performance improvement in the VCR system. In a real application of the AAC system, sub-cooling is clearly allowed by design. Therefore, optimality of the sub-cooling control method at a certain degree of sub-cooling may be possible for the performance improvement in the AAC system.

Compact air-conditioning system

Another way to achieve an energy-efficient AAC system is to make the system as compact as possible; therefore, the frictional losses are reduced and the compressor performs less work in transporting the refrigerant around the cycle. Yan et al. (2012) studied the effects of refrigerant pipeline length on the operational performance of a dual-evaporator air-conditioning (DEAC) system; they indicated that the COP of the DEAC system decreases with an increase in the refrigerant pipeline length as presented in Fig. 24.

From this result, a conclusion can be made on how a compact A/C system, especially because of a short refrigerant pipe, can lead to the development of more energy-efficient AACs.

Extra-circuits air-conditioning system

Multi-circuits system

In practice, large transport A/C systems, such as conventional bus A/C systems, have no thermostat installed, causing the compressor to work continuously at maximum capacity (Mansour et al. 2008). This conventional system used energy inefficiently and severely over-cooling the passenger compartment during partial load conditions. A multi-circuit system offers an attractive solution to this problem where more than one unit of

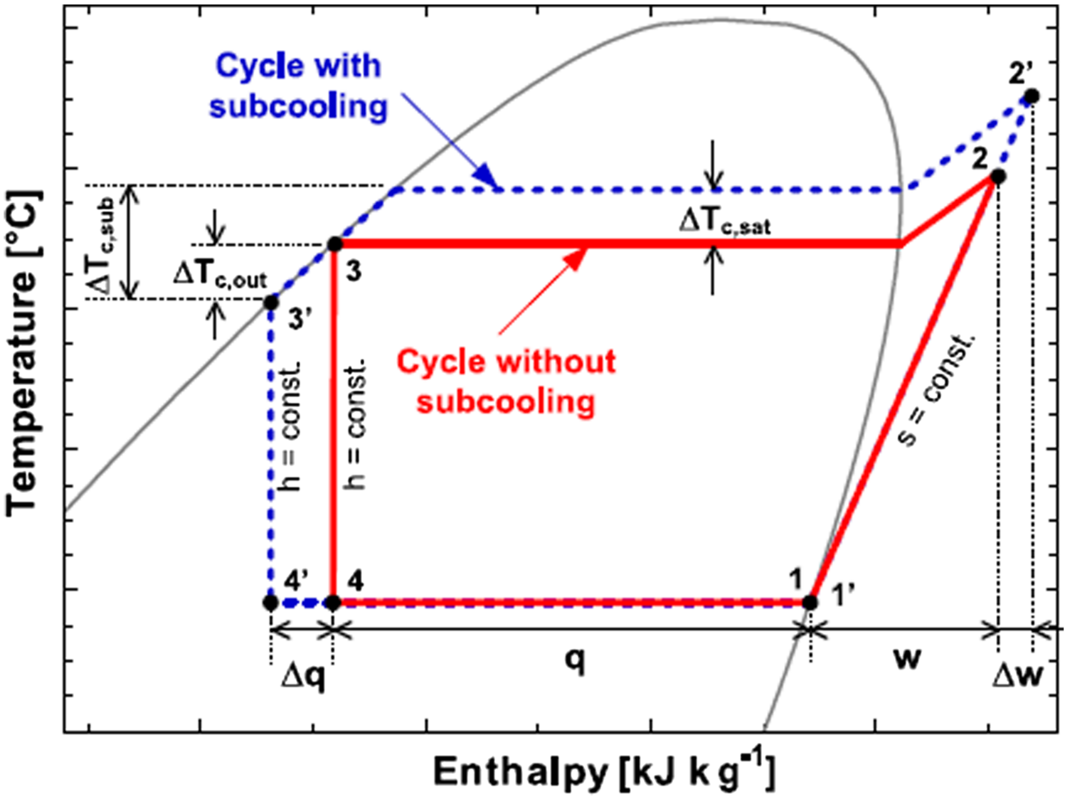


Fig. 23 Comparison between theoretical cycles with and without condenser sub-cooling (Pottker and Hrnjak 2015)

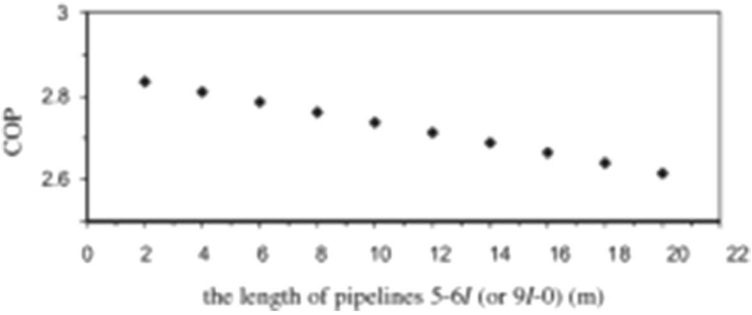


Fig. 24 Variation of COP with the increase in the length of refrigerant pipelines in branch I (Yan et al. 2012)

the A/C circuit can be used; each unit consists of an independent compressor, condenser, and expansion valve while sharing an evaporator.

The main concept behind this system is to control the refrigerant flow in the circuit so that it matches the various cooling loads using few circuits. Therefore, during partial cooling load, such as evening hours or early morning hours, and with a limited number of passengers, one unit of the A/C circuit can be designed to provide adequate cooling to the passengers. A smaller capacity of the compressor is powered up to run the smaller A/C system for smaller cooling loads. However, during peak-cooling load condition, such as the highest ambient temperature in the afternoon and with a full capacity of passengers on board, all the circuits are switched on to provide sufficient cooling to all passengers. More favorable operating conditions during low to high loads are achieved because of a better adjustment of the system to the cooling load. Thus, the A/C system works efficiently and thermal comfort is achieved regardless of any cooling load condition compared with a conventional system.

Mansour et al. (2008) introduced two circuits of a rooftop bus A/C system, with each circuit consisting of an independent compressor, condenser, and expansion valve while sharing an evaporator as shown in Fig. 25. Through an appropriate automatic control strategy, this system is able to provide passengers thermal comfort with up to 31.6 % energy saving and 17 months of payback period compared with the conventional system (Mansour et al. 2008).

With an appropriate control strategy, this multi-circuit A/C system is more suitable for large transport A/C systems, such as busses with an A/C system that runs continuously at maximum capacity. However, introducing extra circuits can increase the initial capital and maintenance costs as well as the weight of the vehicle. Extra weight signifies extra fuel/energy consumption, which reduces the overall performance of the vehicle. Thus, the beneficial effects of multi-circuits are counterbalanced by the extra cost and weight of the vehicle. With no scientific publication related to on-road investigation on the fuel consumption and performance of a vehicle using the multi-circuit A/C system, the actual net effect of this system remains unclear.

Secondary loop system

A secondary-loop (2LP) AAC system is introduced for alternative refrigerants with safety risks, such as flammability (Wang et al. 2010a; Li et al. 2014b), as discussed in the section of "Alternative refrigerants." The potential alternative refrigerants with flammability issues are HFO-1234yf, HFC-152a, HC-290, and HC-600a (Li et al. 2014b). A schematic of the secondary loop refrigeration system is shown in Fig. 26. Rather than the evaporating refrigerant directly cooling down the cabin compartment, the refrigerant/secondary fluid heat exchanger is used to cool down a secondary fluid first to achieve the same purpose. Therefore, a typically variable speed pump is used to circulate the cool secondary fluid from the refrigerant/secondary fluid heat exchanger through a secondary fluid/air heat exchanger.

Wang et al. (2010a) claimed that the 2LP refrigeration system indicates benefits in reducing refrigerant charge, improving energy efficiency, and being able to use natural refrigerants compared with the DX system. Kazachki and Hinde (2006) concluded that for supermarket application, the 2LP system has two advantages over the traditional centralized DX system; these advantages are short liquid-refrigerant supply lines and short vapor-refrigerant return lines.

However, the system encounters efficiency degradation because of the refrigerant/secondary fluid heat exchanger and pump. Therefore, two disadvantages of the 2LP system are the presence of circulation pump and

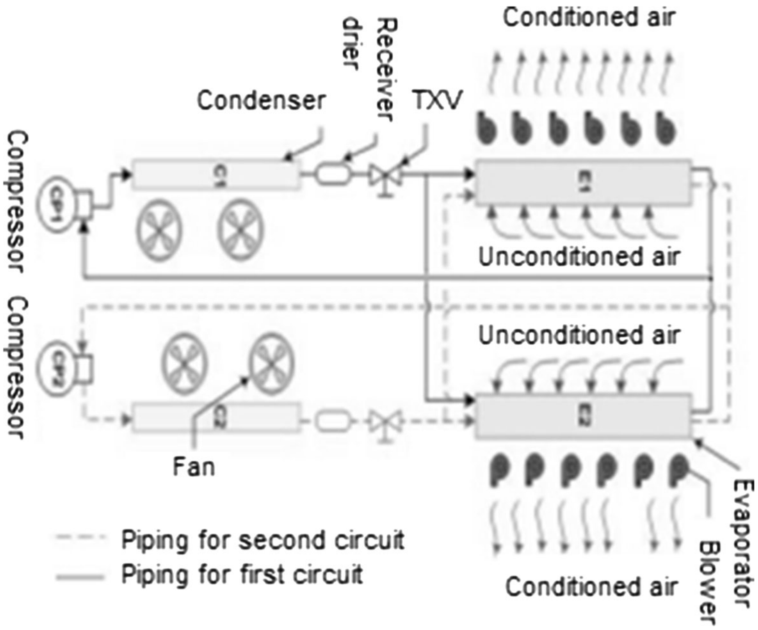


Fig. 25 Schematic of two circuit roof top bus AC system (Mansour et al. 2008)

refrigerant/secondary fluid heat exchanger. The circulation pumps draw energy in addition to the energy used in the DX systems. Then, a portion of this energy results in increased refrigeration load. The refrigerant/secondary fluid heat exchangers introduce an additional temperature differential between the refrigerant and the secondary fluid. The initial capital cost also increases because of these additional components. However, as stated in Table 1, an experimental investigation by Li et al. (2014b) revealed that alternative refrigerants of HFC-152a and HC-290 with 2LP AAC system have better COP and less exergy destruction compared with the DX HFC-134a AAC system. Thus, the balance between the advantages and disadvantages associated with 2LP systems is the key to its success in future AAC systems.

Occupied-zone air-conditioning system

In general, a typical AAC system is equipped with a single evaporator. Using this configuration, Huang et al. (2005) highlighted that the A/C system in the cabin of a small car is separated into the front and rear sections by a flow field with a temperature difference of approximately 6.5 °C; the front and rear cabins are at different temperatures. Therefore, to provide thermal comfort for rear occupants/passengers, the front occupants (i.e., front passenger and driver) may experience overcooling, and when thermal comfort for front occupants is achieved, the rear occupants may experience inadequate cooling. Thus, this system causes inefficient energy usage, and during a full-passenger situation, it can cause thermal discomfort.

The main objective of the AAC system is to provide human thermal comfort in a cabin compartment. Therefore, instead of cooling down the entire cabin as typical conventional AAC systems do, an occupied-zone A/C system only cools down occupied-zone/selected points in the cabin compartment. Therefore, the cooling effect in a certain compartment provides only what is necessary, resulting in optimum thermal comfort and energy saving. Power consumption of the AAC system is drastically reduced especially during lower cooling load and with a limited number of passengers while the passenger thermal comfort is maintained.

Based on the open literature, two types of operational management and control of A/C system can be categorized under occupied-zone A/C system: airflow management or variable air volume (VAV) and variable refrigerant flow/volume (VRF). A typical conventional AAC system operates as a VAV system; however, all of the air outlet vanes are located on the dashboard, especially for small to compact and medium-sized vehicles. The A/C system in the front and rear sections are separated by a flow field; consequently, the front and rear sections are at different temperatures. To optimize the current design, intensive research on this technique continues to be reported worldwide.

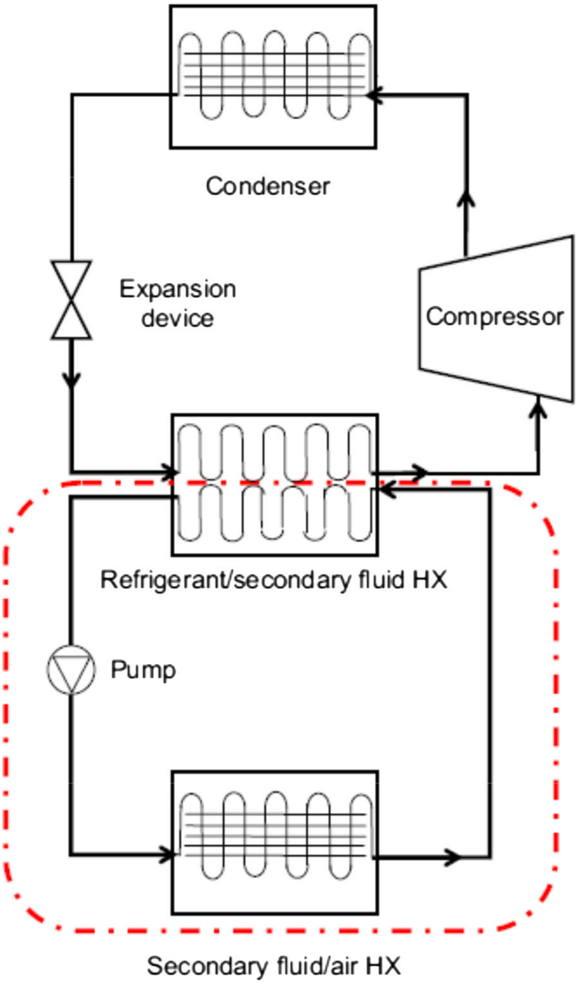


Fig. 26 Schematic of secondary loop refrigeration system (Wang et al. 2010a)

The VRF technique is well accepted as a new option for the VAV system in building space cooling for more energy saving. However, information on the system, especially on control strategies and energy and thermal performance characteristics, are extremely limited because of market potential and company policies. In the case of vehicle application, publications related to VRF are scant because of new research interest in the field of AAC system.

Airflow management technique

Huang et al. (2005), Kaushik et al. (2011), Kwon et al. (2012a), and Gosh et al. (2013) realized the occupied zone or spot cooling of the AAC system through airflow management technique. This technique controls airflow in the vehicle cabin to achieve a regional steady-state temperature. Thus, the controlled airflow of all passengers in different areas of the compartment can be satisfied with respect to their unique temperature demands by delivering a relatively smaller amount of localized air directly to the occupied zone or effectively to the thermally sensitive body parts of the occupant.

Kaushik et al. (2011) demonstrated that all of the three micro-cooling/heating strategies, namely, ventilated seat + seatbelt nozzle active, ventilated seat + neck nozzle active, and ventilated seat + front nozzle active, are capable of delivering sufficient overall thermal comfort at a potentially lower A/C energy consumption and yielding reasonably good estimates of overall thermal sensation and comfort perception levels. Kwon et al. (2012b) developed an occupied-zone HVAC system based on airflow management technique (as presented in Fig. 27) with three zones: driver, front passenger, and rear passenger. Fuel economy evaluation during cooling and heating for the driver-zone mode showed 17–20 % reduction in HVAC power consumption compared with the conventional whole-cabin system (Kwon et al. 2012b).

Consequently, several new models of vehicles now utilize the airflow management technique. For example, in the Proton Exora model shown in Fig. 28, the AAC system is equipped with air outlet vanes in various positions, particularly at the ceiling and rear top right and left.

Variable refrigerant flow air-conditioning system

The compressor in a conventional on/off AAC system requires extra energy to overcome inertia torque and static friction force each time the compressor is switched on. The compressor input power influences the performance of the AAC system (Lee and Yoo 2000; Saiz Jabardo et al. 2002; Kaynakli and Horuz 2003; Wang

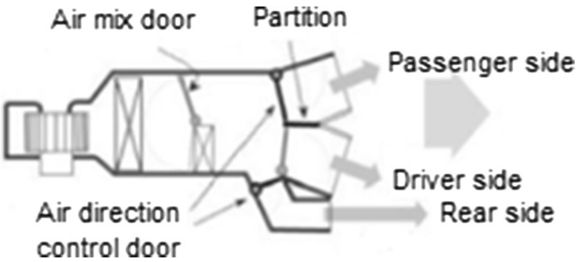


Fig. 27 Occupied-zone HVAC hardware configuration (Kwon et al. 2012b)

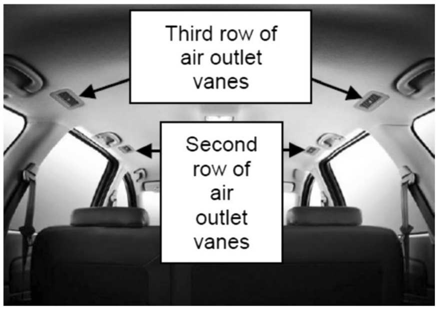


Fig. 28 Air outlet vanes of Proton Exora for second and third rows located at rear top right and left

et al. 2005; Hosoz and Direk 2006; Cuevas et al. 2012); thus, extra input energy signifies considerable losses and reduces the system performance. This problem can be avoided if the compressor operates at few speeds continuously, depending on the cooling load at a time. In general, a higher cooling load leads to high compressor speed and vice versa. The cooling capacity increases with an inflation of refrigerant mass flow rate caused by a surge in the compressor speed of the VCC. This intelligent operation enables better adjustment of the system to various cooling loads. The compressor uses energy efficiently regardless of the time-varying cooling load.

However, the flow rate that is pumped by the compressor under any circumstance in the refrigerant cycle must be consistent; it should complement the flow rate of the expansion valve at its operating condition, following the mass conservation. Thus, simultaneous application of both the EEV and VCC allows the AAC system to respond better at any variation of the cooling load. In this case, cabin thermal comfort is effectively maintained and energy is efficiently consumed, regardless of time-varying weather conditions.

The system that uses this concept is known as VRF or variable refrigerant volume or multi-evaporator system. This system seems promising mainly because of its flexibility for installation, capability for individual climate control, and significant potential for energy savings (Liu and Hong 2010). The VRF system works by controlling the refrigerant volume or flow through VCC, EEV, and multi-evaporators with shared condenser and compressor units. This type of system is developed for multiple zones with various types of cooling load connected to the same refrigerant system. Figure 29 illustrates a VRF system with four indoor units.

This system adjusts its cooling capacity to meet the cooling loads by modulating the refrigerant mass flow rate continuously through the VCC and expansion valves; typically, EEV is used because of its fast response to the variable load, as well as its wide regulated range and high precision (Lui et al. 2007; Wang et al. 2010b). Each indoor unit is responsible for one zone with the shared outdoor (i.e., compressor and condenser) unit and another indoor unit. Therefore, when certain zones have no demand for cooling effect, the refrigerant does not flow to the indoor units in those zones, which are controlled simultaneously by the VCC and EEV. Through this strategy, the VRF system consumes less energy than the common building A/C system; it also provides better indoor thermal comfort as long as it operates under the individual control mode (Aynur 2010).

Zhao et al. (2007) expected that the energy-saving potentials of the VRF systems to be 22.3 and 11.7 % compared with those of the VAV system and fan-coil plus fresh air system, respectively. A comparative energy analysis by Koh et al. (2009) indicated that the peak electrical demand of the VRF system for the cooling season is approximately 60 % of the chiller-based VAV system and 70 % of the packaged VAV system, and the operating energy usage is approximately 53 % of the chiller-based VAV system and 60 % of the packaged VAV system. Abdullah et al. (2011) revealed that the COP of the VRF and centralized chilled water systems used in the same building are 3.3 and 2.0, respectively, which lead to energy savings of up to 39.5 %.

Clearly, the VRF system can be effective because of the more accurate balancing of the cooling load and capacity. The VRF system is probably the best technique to achieve an energy-saving AAC system. This system adopts almost all of the technologies and strategies described in this paper (i.e., efficient VCC, EEV, and occupied-zone air-conditioning strategy). In addition, a VRF system embedded with a micro-channel heat exchanger and optimized with secondary components for a more efficient system is possible.

However, these provided examples of the seasonal performance of a building A/C system may not be directly transferred to the AAC system. Furthermore, an AAC system with multi-evaporators is not necessarily more effective than a single evaporator system and ducts for air transportation in different compartment areas. In such a system, all areas of the evaporator are working even at a lower load, which allows a decreasing temperature difference in the evaporator and higher evaporation temperature (with better efficiency). Of

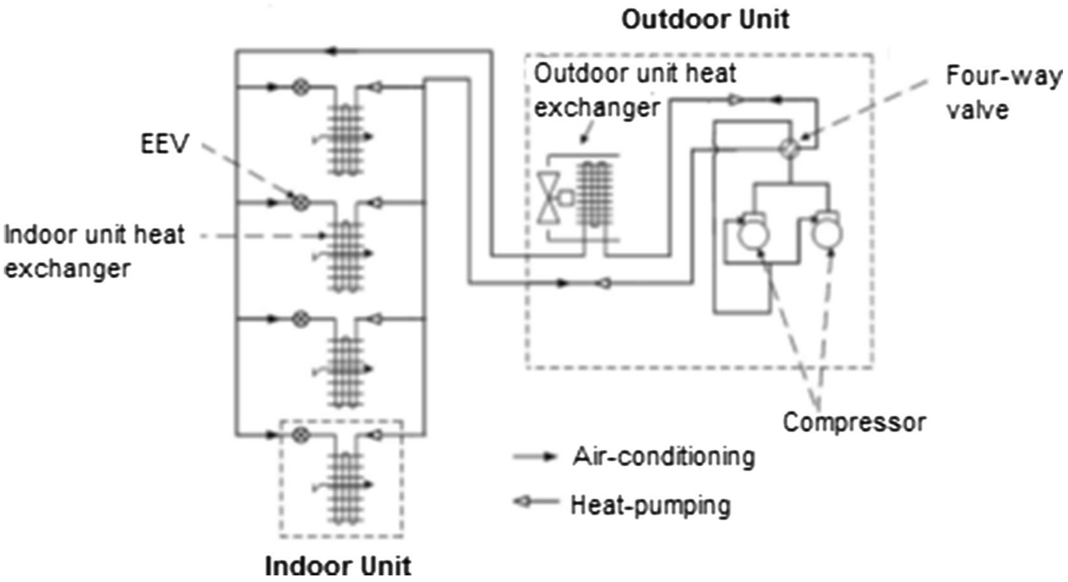


Fig. 29 Schematic of VRF system with four indoor units

course, certain losses in air distribution may occur, but without a more detailed analysis, the system that offers better efficiency is not evident enough, especially considering that all of the required ducts in an AAC are short. In addition to the extra cost because of the more complex system and maintenance work, the VRF system with multi-evaporators for AAC seems impractical. This system with multi-evaporators is more realistic for household and commercial buildings. Although the household refrigerating industry is under strong pressure to offer better efficiency to comply with legislative regulations, systems with multi-evaporators are rare, whereas systems with single evaporator and air ducts are dominant in the market.

However, given energy issues, a VRF system with a single evaporator and different air ducts between the front and rear zones may be a realistic solution for future AAC systems. Using the VRF method can increase the operational efficiency of the compressor, whereas different air ducts for the front and rear zones with individual control methods can efficiently manage the airflow in these zones. By managing the velocity of supplied cold air to the respective cooling zone individually, the system can address the significant difference in the flow field temperature of front and rear zones, as noted by Huang et al. (2005). Thus, the zonal thermal comfort of each zone is possible.

Multi-evaporator VRF A/C systems are more complicated because the compressor drives several evaporators simultaneously (Shen et al. 2000; Wu et al. 2005; Lin and Yeh 2009). Therefore, the operating parameters of one of the evaporators can certainly interfere with those of other evaporators, which makes the control and modeling of the system more complex and difficult. Thus, inappropriate control design can even lead to worse system performance compared with the conventional system. According to Lin and Yeh (2009), VCC and EEV have to be properly feedback-controlled; otherwise, the system may exhibit an even poorer performance than the conventional A/C system using FCC and mechanical expansion valve. For example, in the DEAC system, if the system outputs and control inputs are chosen as the single-evaporator system, it has three control inputs (i.e., one compressor speed and two valve openings) and four system outputs (i.e., two superheating and two evaporating temperatures) (Lin and Yeh 2009). The mismatch between inputs and outputs certainly makes the control design more challenging if performance similar to that of a single evaporator is desired.

However, the VRF with a single evaporator for the AAC system is less complicated in terms of control strategy because of the equal number of input and output control parameters, three in particular. The two input parameters of one valve opening and one compressor speed are matched with two output parameters of one super-heating and one evaporation temperature, respectively. The third input parameter of velocity of the supplied cold air to each cooling zone is controlled by the third output parameter of the desired air temperature in said zones.

In this case, if the load increases, then the super-heating, evaporation temperature, and desired zonal air temperature also increase. If super-heating is controlled at a certain value, that is 4 K, a signal is sent to the EEV to increase the degree of valve opening so that the degree of super-heating can be reduced to its setting value of 4 K. Simultaneously, the speed of the compressor increases to match the additional load and later decreases the evaporation temperature to its initial design value. Furthermore, an increase in zonal air temperature can be reported to the controller, which regulates the air valves or speed of the fan according to the desired zonal temperature. In this proposed control strategy, all surfaces of the evaporator are used continuously, offering the highest evaporation temperature and high efficiency. However, considerable losses occur during air distribution.

Conclusion

An extensive literature review and critical evaluation of the potential energy-efficient technologies and strategies for the AAC system have been conducted. Key features of a few of the most promising technologies and strategies are presented to identify their merits in improving the efficiency of the AAC system. The review of possible energy-efficient technologies and strategies is divided into two categories: component optimization and operation management and control. Certain innovations for the AAC system described in this paper are either under ongoing research or in the conceptualization stage. A growing demand in reducing the energy consumption associated with operating the future AAC system has triggered growing research interest. Thus, these technologies are expected to become substitutes for the conventional systems in the near future.

The compressor produces the highest energy consumption in the vapor compression refrigerant AAC system. Thus, even a slight improvement in its efficiency can lead to significant energy savings. The latest research trend for the energy-efficient compressor is related to the optimization of existing and new compressors. The micro-channel heat exchanger, which does not require electricity for its operation, also offers one of the best options for the energy-efficient AAC system. Although reducing the weight of the micro-channel heat exchanger is a relatively minor adjustment, the effect is significant because the reduced total weight of the vehicle increases the performance of the A/C system and the entire vehicle. The expansion valve can also be optimized through an ejector or EEV. An AAC system-based ejector and EEV are still at the research stage and require further investigation with regard to their feasibility in the automotive industry. Additional components that are either directly installed (i.e., IHX) or indirectly installed (i.e., advanced glazing and insulation) in the A/C system are also reported as a technique to achieve an energy-efficient AAC system. However, the IHX with specific types of refrigerants can also decrease the performance of the A/C system.

The sub-cooling control method is allowed by design for a typical AAC system, but an accurate degree of sub-cooling is necessary to gain maximum performance improvement. The airflow management technique with various locations of air outlet vanes known as VAV is already practiced in the typical AAC system. However, this technique continues to be studied with the intention of optimization for further system performance improvement. Meanwhile, compact and multi-circuits A/C systems are promising concepts for the AAC system. Limited research output has opened opportunities for further research and development.

Certain alternative refrigerants with a suitable AAC design, such as HFC-1234yf with micro-channel parallel flow evaporator, HC-290 with 2LP, and HFC-152a with 2LP, also indicate significant performance improvement compared with the typical DX, HFC-134a AAC system. Given that HFC-134a will be phased out shortly, one of the possible alternative refrigerants proposed in this paper may be the new refrigerant used for the future AAC system. The refrigerant must comply with zero ODP, low GWP, and minimum safety requirements, and should exhibit superior performance compared with other alternative refrigerants.

The VRF technique for the VCRAAC system is a highly promising concept because of its energy-saving characteristic. A VRF system with a single evaporator and different air ducts between its front and rear zones is probably the best way to achieve an energy-efficient AAC system. This proposed system potentially adapts all technologies and strategies described in this paper. However, discussion of this concept for vehicle operation is limited. To date, the research on the AAC system focuses on the VAV system rather than the VRF system.

Although few studies have been conducted on the VRF in the AAC system, more extensive research is required especially in the aspect of suitability, reliability, performance, compressor capacity, and refrigeration flow distribution controls. Therefore, this paper opens up new opportunities for further research and development to be accomplished in the near future.

Acknowledgments The authors are grateful for the support of the Universiti Teknologi Malaysia, Ministry of Education Malaysia, and Universiti Teknikal Malaysia Melaka in providing a platform for research activities in terms of funding (Project No. Q.J130000.2424.00G41).

References

Abd El-Baky, M. A., & Mohamed, M. M. (2007). Heat pipe heat exchanger for heat recovery in air conditioning. *Applied Thermal Engineering*, *27*(4), 795–801.

Abdullah, H., Nitamakwuavan, S. & Jalaludin, A. F. (2011). Energy studies on central and variable refrigerant flow air-conditioning systems. 4th International Meeting of Advances in Thermofluids, IMAT 2011, Melaka, Malaysia; 3 October 2011–4 October 2011. AIP Conference Proceedings 2012, 1440,486–490.

Ahmadzadehtalatapeh, M. (2013). An air-conditioning system performance enhancement by using heat pipe based heat recovery technology. *Scientia Iranica B*, *20*(2), 329–336.

Alahmer, A., Abdelhamid, M., & Omar, M. (2012). Design of thermal sensational and comfort states in vehicles cabins. *Applied Thermal Engineering*, *36*, 126–140.

Alkan, A., & Hosoz, M. (2010). Comparative performance of an automotive air conditioning system using fixed variable capacity compressors. *International Journal of Refrigeration*, *33*(3), 487–495.

Aynur, T. N. (2010). Variable refrigerant flow systems: a review. *Energy and Buildings*, *42*(7), 1106–1112.

Brown, J. S., Samuel, F. Y. M., & Domanski, P. A. (2002). Comparitive analysis of an automotive air conditioning systems operating with CO_2 and R134a. *International Journal of Refrigeration*, *25*, 19–32.

Chen, J., Zhao, Y., & Qi, Z. (2011). New developments in mobile air conditioning systems in China. *Front. Energy*, *5*(1), 53–58.

Cho, H., Lee, H., & Park, C. (2013). Performance characteristics of an automobile air conditioning system with internal heat exchanger using refrigerant R1234yf. *Applied Thermal Engineering*, *61*(2), 563–569.

Cordoba, J., Macias, M., & Manuel Espinosa, J. (1998). Study of the potential savings on energy demand and HVAC energy consumption by using coated glazing for office buildings in Madrid. *Energy and Building*, *27*(1), 13–19.

Cuevas, C., Fonseca, N., & Lemort, V. (2012). Automotive electric scroll compressor: Testing and modeling. *International Journal of Refrigeration*, *35*(4), 841–849.

Desai, A. D., Sapali, S. N., Parthasarathi, V. & Garikipati, V. (2011). Development of energy efficient R-134a eutomotive air conditioning system using internal heat exchanger. Proceedings of the World Congress on Engineering (WCE 2011), Vol. III. London. July 6–8, 2011.

Dieckmann, J. & Mallory, D. (1992). Variable speed compressor, HFC-134a based air conditioning system for electric vehicles. SAE Technical Paper. 920444.

Disawas, S., & Wongwises, S. (2004). Experimental investigation on the performance of the refrigeration cycle using a two-phase ejector as an expansion device. *International Journal of Refrigeration*, *27*(6), 587–594.

Ekren, O., Celik, S., Noble, B., & Krauss, R. (2013). Performance evaluation of a variable speed DC compressor. *International Journal of Refrigeration*, *36*(3), 745–757.

Farrington, R. B., & Rugh, J. (2000). *Impact of vehicle air-conditioning on fuel economy, tailpipe emissions, and electric vehicle range*. D.C.:Earth Technologies Forum Washington.

Farrington, R. B., Rugh, J. P. & Barber, G. D. (2000). Effect of solar-reflective glazing on fuel economy, tailpipe emissions, and thermal comfort. SAE Technical Paper. 2000–01–2694.

Fischer, S. K. (1995). *Comparison of global warming impacts of automobile air-conditioning concepts*. Washington: 1995 International CFC and Halons Alternative Conference.

Fritsch, R. (1991). Automotive insulating glass—improvements in comfort. SAE Technical Paper. 910546.

Gasworth, S. & Tankala, T. (2011). Reduced steady state heating and air conditioning loads via reduced glazing thermal conductivity. SAE Technical Paper. 2011–01–0126.

Ghosh, D., Wang, M., Wolfe, E., Chen, K., Kaushik, S., & Han, T. (2013). Energy efficient HVAC system with spot cooling in an automobile—design and CFD analysis. *SAE Int. J. Passeng. Cars - Mech. Syst.*, *5*(2), 885–903.

Han, X. H., Li, P., Xu, Y. J., Zhang, Y. J., Wang, Q., & Chen, G. M. (2013). Cycle performances of the mixture of HFC-161 + HFC-134a as substitution of HFC-134a in automotive air conditioning system. *International Journal of Refrigeration*, *36*, 913–920.

Han, Y., Liu, Y., Lia, M., & Huang, J. (2012). A review of development of micro-channel heat exchanger applied in air-conditioning system. *Energy Procedia*, *14*, 148–153.

Hosoz, M., & Direk, M. (2006). Performance evaluation of an integrated automotive air conditioning and heat pump system. *Energy Conversion and Management*, *47*(5), 545–559.

Huang, C. C. D. (1998). *A dynamic computer simulation model for automobile passenger compartment climate control and evaluation*. PhD Dissertation:Michigan Technologival University.

Huang, K. D., Tzeng, S. C., Jeng, T. M., & Chiang, W. D. (2005). Air-conditioning system of an intelligent vehicle-cabin. *Applied Energy*, *83*(6), 545–557.

Jensen, J. B., & Skogestad, S. (2007). Optimal operation of simple refrigeration cycles part 1: degrees of freedom and optiamality of subcooling. *Computer and Chemical Engineering*, *31*, 712–721.

Johnson, V. H. (2002). Fuel used for vehicle air-conditioning: A state-by-state thermal comfort-based approach. SAE Technical Paper. 2002–01–1957.

Kahn Ribeiro, S., Kobayashi, S., Beuthe, M., Gasca, J., Greene, D., Lee, D. S., Muromachi, Y., Newton, P. J., Plotkin, S., Sperling, D., Wit, R. & Zhou, P. J. (2007). Transport and its Infrastructure. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)]. Cambridge, United Kingdom and New York, USA: Cambridge University Press.

Kairouani, L., Elakhdar, M., Nehdi, E., & Bouaziz, N. (2009). Use of ejectors in a multi-evaporator refrigeration system for performance enhancement. *International Journal of Refrigeration*, *32*(6), 1173–1185.

Kaushik S, Chen K. H., Han T. & Khalighi B. (2011). Micro-cooling/heating strategy for energy efficient HVAC system. SAE Technical Paper. 2011–04–12.

Kaynakli, Ö., & Horuz, I. (2003). An experimental analysis of automotive air conditioning system. *Int. Comm. Heat Mass Transfer*, *30*(2), 273–284.

Kazachki, G., & Hinde, D. (2006). Secondary coolant systems for supermarkets. *ASHRAE Journal*, *48*(9), 34–46.

Kim, M. H., Lee, S. Y., Mehendale, S. S., & Webb, R. L. (2003). Microchannel heat exchanger design for evaporator and condenser applications. *Advances in Heat Transfer*, *37*, 297–429.

Klein, S. A., Reindl, D. T., & Brownell, K. (2000). Refrigeration system performance using liquid-suction heat exchangers. *International Journal of Refrigeration*, *23*, 588–596.

Koh, J., Zhai, J. Z., & Rivas, J. A. (2009). Comparative energy analysis of VRF and VAV systems under cooling mode. In *ASME 3rd international conference on energy sustainability, ES2009; San Francisco, United States, 19–23 July 2009, vol. 1* (pp. 411–418).

Konz, M. (2007). *A generic simulation of energy consumption of automobile air conditioning systems*. M Tech Eng Thesis: Nelson Mandela Metropolitan University.

Kwon, L., Hwanga, Y., Radermachera, R., & Kim, B. (2012a). Field performance measurements of a VRF system with sub-cooler in educational offices for the cooling season. *Energy and Buildings*, *49*, 300–305.

Kwon, C., Lee, C., Foster, L. & Kwon, J. (2012b). Development of an energy-saving occupied-zone HVAC system (OZ HVAC). SAE Technical Paper 2012–01–0320.

Lawrance, N., & Elbel, S. (2014). Experimental investigation of a two-phase ejector cycle suitable for use with low-pressure refrigerants R134a and R1234yf. *International Journal of Refrigerant*, *38*, 310–322.

Lee, G. H., & Yoo, J. Y. (2000). Performance analysis and simulation of automobile air conditioning system. *International Journal of Refrigerant*, *23*(3), 143–254.

Lee, J. S., Kim, M. S., & Kim, M. S. (2011). Experimental study on the improvement of a CO_2 air conditioning system performance using an ejector. *International Journal of Refrigeration*, *34*, 1614–1625.

Lee, J. S., Kim, M. S., & Kim, M. S. (2014). Studies on the performance of a CO_2 air conditioning system using an ejector as an expansion device. *International Journal of Refrigeration*, *38*, 140–152.

Li, G. (2015). Comprehensive investigations of life cycle climate performance of packaged air source heat pumps for residential application. *Renewable & Sustainable Energy Reviews*, *43*, 702–710.

Li, G., Alabdulkarem A., Hwang, Y., Radermacher, R. (2014a). Drop in life cycle climate performance of low GWP R-410A alternatives for heat pumps. 11th IIR-Gustav Lorentzen Conference ON Natural Refrigerants – GL2014.

Li, G., Eisele, M., Lee, H., Hwang, Y., & Radermacher, R. (2014b). Experimental investigation of energy and exergy performance of secondary loop automotive air-conditioning systems using low-GWP (global warming potential) refrigerants. *Energy*, *68*, 819–831.

Li, X., Chen, J., Chen, Z., Liu, W., Hu, W., & Liu, X. (2004). A new method for controlling flow in automobile air conditioning. *Applied Thermal Engineering*, *24*(7), 1073–1085.

Lin, J. L., & Yeh, T. J. (2009). Control of multi-evaporator air-conditioning systems for flow distribution. *Energy Conversion and Management*, *50*(6), 1529–1541.

Liu, X., & Hong, T. (2010). Comparison of energy efficiency between variable refrigerant flow systems and ground source heat pump systems. *Energy and Buildings*, *42*(5), 584–589.

Lui, J., Chen, J., Ye, Q., & Chen, Z. (2007). A new model for depicting mass flow rate characteristic of electronic expansion valves. *Experimental Thermal and Fluid Science*, *32*(1), 214–219.

Mansour, M. K., Musa, M. N., Wan Hassan, M. N., & Saqr, K. M. (2008). Development of novel control strategy for multiple circuit roof top bus air conditioning system in hot humid countries. *Energy Conversion and Management*, *49*(6), 1455–1468.

Meyer, J. J., Southwood, J. & Chan, M. (2003). Energy efficient thermal vehicle for reduced climate system load. Vehicle Thermal Management Systems, VTMS 6, Brighton, United Kingdom. 18 May 2003–21 May 2003, 149–157.

Mitsui, M. (1987). Improvement of refrigerant flow control method in automotive air conditioners. SAE Technical Paper. 870029.

Murakami, H., Kataoka, H., Honda, Y., Morimoto, S., & Takeda, Y. (2001). Highly efficient brushless motor design for an air-conditioner of the next generation 42 V vehicle, industry applications conference, 2001. *Thirty-Sixth IAS Annual Meeting. Conference Record of the IEEE*, *2001*(1), 461–466.

Ooi, K. T. (2005). Design optimization of a rolling piston compressor for refrigerators. *Applied Thermal Engineering*, *25*(5–6), 813–829.

Park, C. Y., & Hrnjak, P. (2008). Experimental and numerical study on microchannel and round-tube condensers in a R410A residential air-conditioning system. *International Journal of Refrigeration*, *31*(5), 822–831.

Park, S. K., Kim, H., Ahn, H. & Park, H. S. (2006). Study on the reduction of fuel consumption in the A/C system, used variable displacement swash-plate compressor and the performance improvement by field test. SAE Technical Paper. 2006–01–0164.

Pottker, G., & Hrnjak, P. (2015). Experimental investigation of the effect of condenser sub-cooling in R134a and R1234yf air conditioning systems with and without internal heat exchanger. *International Journal of Refrigerant*, *50*, 104–113.

Qi, Z. (2013). Experimental study on evaporator performance in mobile air conditioning system using HFO-1234yf as working fluid. *Applied Thermal Engineering*, *53*, 124–130.

Qi, Z., Chen, J., Chen, Z., Hu, W., & He, B. (2007). Experimental study of an auto-controlled automotive air conditioning system with an eternally-controlled variable displacement compressor. *Applied Thermal Engineering*, *27*, 927–933.

Qi, Z., Zhao, Y., & Chen, J. (2010). Performance enhancement study of mobile air conditioning system using micro-channel heat exchangers. *International Journal of Refrigeration*, *33*(2), 301–312.

Ribeiro, G. B., Barbosa Jr., J. R., & Prata, A. T. (2012). Performance of microchannel condensers with metal foams on the air-side: application in small-scale refrigeration systems. *Applied Thermal Engineering*, *36*, 152–160.

Roscher, M. A., Leidholdt, W., & Trepte, J. (2012). High efficiency energy management in BEV applications. *Electrical Power and Energy Systems*, *37*(1), 126–130.

Saiz Jabardo, J. M., Gonzales Mamani, W., & Ianella, M. R. (2002). Modeling and experimental evaluation of an automotive air conditioning system with a variable capacity compressor. *International Journal of Refrigerant*, *25*(8), 1157–1172.

Sand, J. R. & Fischer, S. K. (1997). Total environmental warming impact (TEWI) calculations for alternative automotive air-conditioning systems. 1997 SAE International Congress. Detroit.

Shen, B., Su, Z. & Wang, Y. (2000). Research on characteristic of double-evaporator in VRV air conditioner. International Refrigerant and Air Conditioning Conference 2000, paper 475.

Sukri, M. F., Salim, M. A., Mohd Rosli, M. A., Azraai, S., & Mat Dan, R. (2012). An analytical investigation of overall thermal transfer value on commercial building in Malaysia. *International Review of Mechanical Engineering*, *6*(5), 1050–1056.

Sumeru, K., Nasution, H., & Ani, F. N. (2012). A review on two-phase ejector as an expansion device in vapor compression refrigeration cycle. *Renewable and Sustainable Energy Reviews*, *16*(7), 4927–4937.

Sumeru, K., Sulaimon, S., Nasution, H., & Ani, F. N. (2014). Numerical and experimental study of an ejector as an expansion device in split-type air conditioner for energy savings. *Energy and Buildings*, *79*, 98–105.

Tan, K. M., & Ooi, K. T. (2011). A novel revolving vane compressor with a fixed-vane. *International Journal of Refrigeration*, *34*(8), 1980–1988.

Teh, Y. L., & Ooi, K. T. (2009a). Theoretical study of a novel refrigeration compressor—part I: design of the revolving vane (RV) compressor and its frictional losses. *International Journal of Refrigeration*, *32*(5), 1092–1102.

Teh, Y. L., & Ooi, K. T. (2009b). Theoretical study of a novel refrigeration compressor—part II: performance of a rotating discharge valve in the revolving vane (RV) compressor. *International Journal of Refrigeration*, *32*(5), 1103–1111.

Teh, Y. L., & Ooi, K. T. (2009c). Theoretical study of a novel refrigeration compressor—part III: leakage loss of the revolving vane (RV) compressor and a comparison with that of the rolling piston type. *International Journal of Refrigeration*, *32*, 945–920.

Teh, Y. L., & Ooi, K. T. (2009d). Experimental study of the revolving vane (RV) compressor. *Applied Thermal Engineering*, *29*(14–15), 3235–3245.

Tian, C., Dou, C., Yang, X., & Li, X. (2005). Instability of automotive air conditioning system with a variable displacement compressor. Part 1. Experimental investigation. *International Journal of Refrigeration*, *28*(7), 1102–1110.

Thornton, J. W., Klein, S. A., & Mitchell, J. W. (1994). Dedicated mechanical subcoolmg design strategies for supermarket applications. *International Journal of Refrigeration*, *17*(8), 508–515.

Tamura, T., Yakumaru, Y., & Nishiwaki, F. (2005). Experimental study on automotive cooling and heating air conditioning system using CO_2 as a refrigerant. *International Journal of Refrigeration*, *28*, 1302–1307.

Türler, D., Hopkins, D. & Goudey, H. (2003). Reducing vehicle auxiliary loads using advanced thermal insulation and window technologies. SAE Technical Paper. 2003–01–1076.

Umezu, K. (2010). *Air-conditioning system for electric vehicles (i-MiEV)*. SAE Automotive Refrigerant & System Efficiency Symposium.

Wang, K., Eisele, M., Hwang, Y., & Radermacher, R. (2010a). Review of secondary loop refrigeration systems. *International Journal of Refrigeration*, *33*, 212–234.

Wang, S., Gu, J., Dickson, T., Dexter, J., & McGregor, I. (2005). Vapor quality and performance of an automotive air conditioning system. *Experimental Thermal and Fluid Science*, *30*, 59–66.

Wang, Z., Xu, Z., Gao, F. & Rui, S. (2010b). Experimental study on flow characteristics of the electronic expansion valve with variable condition. Power and Energy Engineering Conference (APPEEC) 2010 Asia-Pacific, Chengdu, 28–31 March 2010, 1–4.

Wongwises, S, Kamboon, A. & Orachon, B. (2006). Experimental investigation of hydrocarbon mixture to replace HFC-134a in an automotive air conditioning system. Energy Conversion and Management, 47, 1644–1659.

Wu, C., Xingxi, Z., & Shiming, D. (2005). Development of control method and dynamic model for multi-evaporator air conditioners (MEAC). *Energy Conversion and Management*, *46*(3), 451–465.

Wu, M., Yuan, X. R., Xu, Y. J., Qiao, X. G., Han, X. H., & Chen, G. M. (2014). Cycle performance study of ethyl fluoride in the refrigerant system of HFC-134a. *Applied Energy*, *136*, 1004–1009.

Yan, J., Cai, W., Zhao, L., Li, Y., & Lin, C. (2013). Performance evaluation of a combined ejector-vapor compression cycle. *Renewable Energy*, *55*, 331–337.

Yan, P., Xiangguo, X., Liang, X., & Shiming, D. (2012). A modeling study on the effects of refrigerant pipeline length on the operational performance of a dual-evaporator air conditioning system. *Applied Thermal Engineering*, *39*, 15–25.

Yang, M. H., & Yeh, R. H. (2015). Performance and exergy destruction analyses of optimal subcooling for vapor-compression refrigeration systems. *International Journal of Heat and Mass Transfer*, *87*, 1–10.

Yu, R., Sommers, A. D., & Okamoto, N. C. (2013). Effect of a micro-grooved fin surface design on the air-side thermal-hydraulic performance of a plain fin-and-tube heat exchanger. *International Journal of Refrigeration*, *36*(3), 1078–1089.

Zhang, H., Dai, L., Xu, G., Li, Y., Chen, W., & Tao, W. (2009). Studies of air-flow and temperature fields inside a passenger compartment for improving thermal comfort and energy saving. Part 1: test/numerical model and validation. *Applied Thermal Engineering*, *29*(10), 2022–2027.

Zhao, Y. P., Wu, J. Y., Wang, R. Z., & Shiochi, S. (2007). Energy simulation in the variable refrigerant flow air-conditioning system under cooling conditions. *Energy and Buildings*, *39*(2), 212–220.