

Advances on heat pump applications for electric vehicles

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(Received February 7, 2017, Revised August 23, 2017, Accepted January 2, 2018)

Abstract. A detailed literature review is presented for the applications of the heat pump technologies on the electric vehicles Heating, Ventilation and Air Conditioning (HVAC) system. Due to legal regulations, automotive manufacturers have to produce more efficient and low carbon emission vehicles. Electric vehicles can be provided these requirements but the battery technologies and energy managements systems are still developing considering battery life and vehicle range. On the other hand, energy consumption for HVAC units has an important role on the energy management of these vehicles. Moreover, the energy requirement of HVAC processes for different environmental conditions are significantly affect the total energy consumption of these vehicles. For the heating process, the coolant of internal combustion (IC) engine can be utilized but in electric vehicles, we have not got any adequate waste heat source for this process. The heat pump technology is one of the alternative choices for the industry due to having high coefficient of performance (COP), but these systems have some disadvantages which can be improved with the other technologies. In this study, a literature review is performed considering alternative refrigerants, performance characteristics of different heat pump systems for electric vehicles and thermal management systems of electric vehicles.

Keywords: heat pump system; electric vehicle; air conditioning system

1. Introduction

In electric vehicles, the HVAC system has the most power consumption after the electrical motor (Vatanparvar *et al.* 2015). On the other hand, pure electric vehicles have no waste heat to satisfy the vehicle's heat demand. Electric motor's waste heat is also insufficient to satisfy heating process of the cabin. The usage of energy for the heating significantly affects the mileage because more electric energy is needed from the batteries. Amount of waste heat and heat demand in different type of electric vehicles is shown in Fig. 1 (Hainzmaier *et al.* 2015).

Therefore, for the aim of heating the cabin, there are some alternative systems developed such as heat pump systems, thermoelectric elements, electrical resistance heaters etc. (Antonijevic and Heckt 2004, Lemort *et al.* 2012, Qi 2014). But there are some significant deficiencies in using

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electric heaters; these elements consume too much energy from the battery and reducing the battery's life (Antonijevic and Heckt 2004, Lemort *et al.* 2012, Qi 2014, Li *et al.* 2014, Vatanparvar *et al.* 2015, Hainzmaier *et al.* 2015). High voltage Positive Temperature Coefficient (PTC) heaters are used in most of commercial electric vehicles because of quick warm-up performance but these heaters' efficiency is low and using of them is considerably decreasing the mileage of the vehicles. To overcome these problems, as mentioned above, many researches as well as the automotive manufacturers (Fig. 2) have been focused on the heat pump air conditioning systems (Kondo *et al.* 2011, Green Car Congress 2012, Qin *et al.* 2015, Groupe Renault 2016).

	Mild Hybrid	Hybrid	Plug-In Hybrid	Range Extender	Electric Vehicle
Electric Range	●	●	●	●	●
Engine Waste Heat	●	●	●	●	○
Required Heat Demand	●	●	●	●	●

Fig. 1 Heat demand on electrification (Hainzmaier *et al.* 2015)

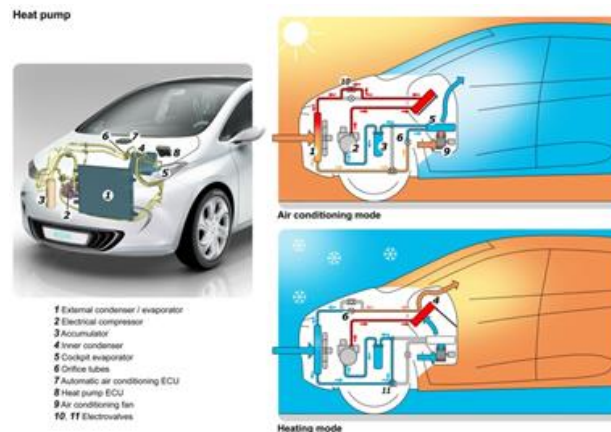


Fig. 2 Heat pump system in Renault ZOE (Groupe Renault 2016)

The heat pump system is very attracting method for providing supplemental heat to the cabin which is performed by reversing the direction of the refrigerant flow in traditional automotive air conditioning system (Lee *et al.* 2013). Vapor compression cycle is common used for the heat pump system and for example, the system shown in Fig. 3 consists of five basic components: indoor and outdoor heat exchanger, compressor, expansion valve and four-way switching valve. This system's most remarkable part is four-way valve and it can change the direction of the refrigerant cycle providing that both heating and cooling modes. During the cooling process, compressed refrigerant passes through the four-way valve and goes to the outdoor exchanger which condensates refrigerant to a liquid phase. For this reason, in cooling mode, indoor heat exchanger acts as an evaporator and outdoor heat exchanger acts as a condenser. The liquid refrigerant passes through

the expansive valve and goes to the indoor heat exchanger which evaporates refrigerant to provide the cooling of indoor environment, and finally refrigerant returns to compressor after passing through the four-way valve.

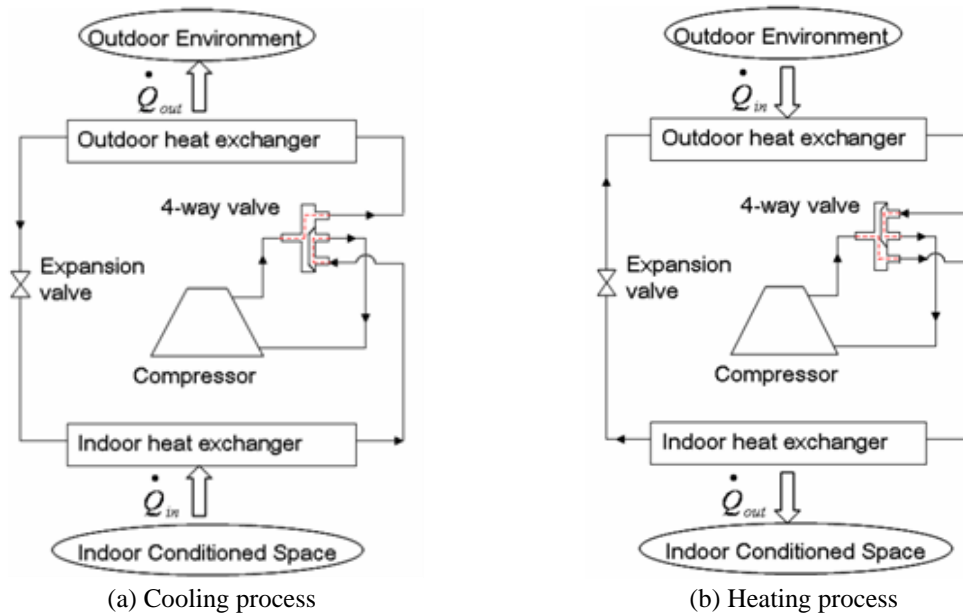


Fig. 3 Schematic view of a typical heat pump system (Lee and Lee 2013)

In heating mode, indoor and outdoor heat exchangers change the operation principles. For the heating mode, the discharged refrigerant vapor provided by compressor enters the indoor heat exchanger, rejects heat to the indoor environment and condenses into a liquid-phase. Refrigerant passes through the expansion valve and liquid flow turn into two phase flow and enters the outdoor heat exchanger which draws heat from the outdoor environment. The evaporated refrigerant vapor comes back to the compressor at the end of the process (Wang 2008). The important parameter affects the heat pump system performance is the ambient temperature, moreover the heat pump system has to work efficiently under severe weather conditions. Particularly in winter conditions where maximum heating capacity is needed the heat pump's coefficient of performance decreases.

In this paper, a comprehensive review on the research area of the automotive heat pump system was performed considering the classification entitled as: i) Current and alternative refrigerants ii) Performance tests of the components of heat pump systems iii) Thermal management of electric vehicles.

2. Current and alternative refrigerants

2.1 Advanced R-134a systems

R-134a is still widely used refrigerant in vehicle AC systems, but today's refrigerants with a

low global warming are emerged due to legal regulations in the automotive industry. R-1234yf has similar thermodynamic properties and it has also advantages in view of global warming potential compared to the R-134a (Reasor *et al.* 2010). Dehumidifying heat pump system with an electric-driven compressor was developed to reduce power consumption of electric vehicle air conditioning system which is used R-134a (Suzuki and Ishii 1996). Semi-theoretical cycle models were used to evaluate the comparative performance of R-134a and CO₂ refrigerants for automotive air conditioning system and the simulation results showed that R-134a having a better COP than CO₂ and the difference in COP depends on the compressor speed and ambient temperature (Brown *et al.* 2002).

2.2 Advanced R-744 systems

CO₂ since it is not a new refrigerant but the properties of CO₂ are quite different considering with conventional ones. For instance, operating pressures in these systems are mainly 5–10 times higher than the conventional refrigerants, and as a result of this higher pressure, several effects that influence the design of components and their performance were emerged. (Kim *et al.* 2003).

R-744 was also one of the first refrigerants in the earliest heat pump and refrigeration systems. There were a lot of researches focused on the use of R-744 in a transcritical cycle. These researches showed that transcritical R-744 cycles can perform well for automotive air conditioning, heat pump water heater and some commercial refrigeration applications. In terms of environmental regulations, transcritical R-744 heat pump and refrigeration systems can be applicable in general (Ma *et al.* 2013).

A novel R-744 heat pump system was provided for use in fuel cell vehicles by considering different heat exchangers arrangements. Experimental study was performed for both steady and transient state conditions at different operating conditions. According to these results, changing the positions of the evaporator and the radiator as exterior heat exchanger had an important role on the heating performance. With changing the positions, heating capacity increased by 35-54% and the COP increased 16-22% comparing to the baseline design. On the other hand, at the new positioning design, the cooling capacity decreased by 40-60% and the COP fairly decreased by 43-65% compared to conventional one (Kim *et al.* 2007). In another research, for medium-sized cars, an efficient automotive heating and cooling air conditioning system using R-744 as refrigerant was developed and a prototype was manufactured. Performance of this system was equal or exceeding that of a system using R-134a as refrigerant (Tamura *et al.* 2005).

From the comparative results of the refrigerants R-134a and CO₂, the electrical air conditioning system using R-744 with an inverter driven compressor had better performance compared to the conventional one using refrigerant R-134a. This improved electrical air conditioning system for fuel cell electric vehicle had better properties for cooling loads of different driving conditions mentioned in this study (Lee *et al.* 2012). The performance characteristics of air conditioning system using refrigerant CO₂ as an alternative to conventional one is performed for hybrid electric vehicles. From the results of this experimental study, the cooling capacity and COP of this developed system can be provided the desired conditions for hot weather conditions (Lee and Lee 2013).

2.3 Other systems

The industry and researchers focus on the other options such as R-152a, R-161, hydrocarbon

mixtures, and also CO₂ (R-744). There are too many researches in available literature about comparison of the performances of different refrigerants (Scherer *et al.* 2003, Jarahnejad 2012, Qi 2013, Wang 2014, Pottker and Hrnjak 2015).

R-152a is an alternative refrigerant to R-134a in mobile air conditioning systems because of its global warming potential. Simulated performance of R152a and hydrocarbon refrigerants were evaluated as a potential refrigerant in mobile air conditioning systems and comparative assessment of the performance of a secondary loop system using these refrigerants was provided. The advantages of this secondary loop system can be obtained in this reference (Ghodbane 1999).

CO₂ heat pump with gas injection experimental study was investigated. The CO₂ heat pump with gas injection system was tested by varying gas injection ratios and outdoor temperatures. According to the test results, the heating capacity and COP increased with the increase of the gas injection ratio and were improved by 45% and 24% respectively (Baek *et al.* 2008). Gas-mixing heat pump air conditioning system was evaluated for pure electric vehicles under low outdoor temperature. The mathematical model of the system was generated and the system performance was computed by using this model in this study (Li *et al.* 2014).

Characteristics of the refrigerant cycle of refrigerants R-134a and R-1234yf with same automotive refrigeration system was investigated. In this study, for improving performance of refrigerant R1234yf, an internal heat exchanger was added to the system and this addition helps to evaluate the level of performance improvement. The results show that the cooling capacity and COP of the R-1234yf system without internal heat exchanger decrease thus, an internal heat exchanger can be used for increasing the performance of R-1234yf refrigeration system (Cho *et al.* 2013).

Thermo-physical properties of R-1234yf are similar to R-134a and it gives an advantage to replace of R-134a in automotive HVAC systems. In order to use R-1234yf in conventional R-134a HVAC systems some minor modifications are adequate (Reasor *et al.* 2010, Zilio *et al.* 2011). Most of electric vehicles used electrical heating elements for heating process. But these elements decrease battery life and vehicle maximum range. Thus, researchers focused on HVAC systems which worked as a heat pump system. Comparative study of heat pump system using R-134a and PTC heater for electric vehicles was investigated considering energy consumption. As it is known, PTC heaters are commonly preferred because of have simple structure and quick responding time (Shin *et al.* 2015, Shin *et al.* 2016). It was found that the heating capacity of AHP is inadequate when the ambient temperature is equal and below to -10°C, under these severe conditions small capacity of electric PTC heater can be used with AHP system to optimizing the energy usage and to provide thermal comfort (Lee 2015).

2.4 Comparison studies of systems

Mobile air conditioning systems using R-134a and R-1234yf as refrigerants were investigated in a heat pump bench tester and COP and capacity of R-1234yf were up to 2.7% and 4% lower than those of R-134a, respectively. The compressor discharge temperature of R-1234yf is 6.4-6.7°C lower than R-134a. According to these results, R-1234yf can be used as a long term environmentally friendly solution in mobile air conditioning systems due to its environmentally properties with acceptable performance (Lee and Jung 2012).

Another comparative results were studied considering design and performance criteria for optimized internal heat exchanger. Moreover, some design parameters for the internal heat exchanger were recommended for application to each refrigerant. According to these test results,

Table 1 Researches about refrigerants available in the literature

Authors	Published Year	Refrigerants	Test Conditions
J. Steven Brown Samuel F. Yana-Motta Piotr A. Domanski	2002	R-744 (CO ₂) R-134a	Compressor speed: 1000 (rpm) Ambient temperature: 32.2, 48.9 (°C)
Main Results			
1-CO ₂ has lower COP than R-134a. 2-The COP disparity values 21% and 34% at 32.2 and 48.9 respectively 3-The disparity of COP depends on compressor speed and ambient temperature			
L. P. Scherer M. Ghodbane J. A. Baker P. S. Kadle	2003	R-1234yf R-152a	Ambient temperature: -18 (°C) Vehicle speed: 48/113 (kph)
Main Results			
1-Both of R-152a and R-134a heat pump systems have almost identical performance and capacity 2-Heat pump capacities of both R-152a and R-134a systems at steady state speeds of 48 kph and 113 kph road load are 8.8 kW at -18°C			
Claudio Zilio J. Steven Brown Giovanni Schiochet Alberto Cavallini	2011	R-1234yf R-134a	Compressor speed: 900-4000 (rpm) Evaporator air inlet temperature: 15/25/35 (°C) Evaporator air inlet relative humidity: %80/80/40 Condenser air inlet temperature: 5/25/35 (°C) Evaporator/Condenser air volumetric flow rate: 400/1580 (m ³ /h)
Main Results			
1-Making minor modifications to the system, cooling capacity with using R-1234yf is significantly lower than the baseline R-134a one 2-Making major modifications to the system such as enhancing condenser/evaporator, the COP of R-1234yf system higher than the baseline R-134a for equal cooling capacities			
M. Jarahnejad	2012	R-1234yf R-1234ze R-134a	Condensing temperature: 30/40 (°C)
Main Results			
1-Refrigerants like CO ₂ , R152a, R-1234yf and R-1234ze have low GWP and acceptable potential to replace the common refrigerants 2-R-1234ze has about 3% higher pressure ratio than R-134a while R-1234yf has 9% lower pressure ratio than R-134a 3-COP of R-1234yf is lower than R-134a at both 30 and 40°C			
Moo-Yeon Lee Ho-Seong Lee Hong-Phil Won	2012	R-744 (CO ₂) R-134a	Compressor speed: 3000,4000,5000,6000 (rpm) Displacement of comp.: 7.5 (cc/rev) Outdoor air temperature: 27, 35, 42 (°C) Air flow rate: 2.0, 4.0 (m/s) Vehicle condition/air velocity: Idle/2.3 and 100/6.0 [(km/h)/(m/s)]
Main Results			
1-Cooling capacity increases 30.3% up to 6.4 kW compared to R-134a 2-COP increases 36.8% up to 2.5 compared to R-134a 3-Air conditioning system using R-744 showed better performance approximately 24% than the conventional air conditioning system with R-134a at all compressor			

Table 1 Continued

Zhaogang Qi	2013	R-1234yf R-134a	Air inlet temperature: 35/38/40 (°C) Relative Humidity: %40-60
Main Results			
1-In laminated plate evaporator, R-134a has a better heat transfer and flow rate performance than R-1234yf			
2-In parallel flow evaporation, cooling capacity of R-1234yf is comparable and/or higher than R-134a			
Honghyun Cho Hoseong Lee Chasik Park	2013	R-1234yf R-134a	Compressor speed: 200/1800/2500 (rpm) Indoor temperature: 27/19.5 (°C) Outdoor temperature: 35/24 (°C)
Main Results			
1-Under the same automotive refrigeration system with using R-1234yf showed lower power consumption and cooling capacity than R-134a			
2-Adding an internal heat exchanger to the system affected the cooling capacity and COP			
Ho-Seong Lee Moo-Yeon Lee	2013	R-744 (CO ₂) R-134a	BDC (Belt driven compressor) speed: 900-1800 (rpm) EDC (Electricity driven compressor) speed: 2000-6000 (rpm)
Main Results			
1-Cooling capacity and cooling COP are over 5.0 kW and 2.0 for both the battery driving mode and the engine driving mode			
2-The cooling COP of the electrical air-conditioning system using an inverter driven compressor was higher than that of the belt driven air-conditioning system using R-744 (CO ₂) and R-134a			
D. Lee	2015	R-134a	Compressor speed: 1000-7000 (rpm) Outside air temperature: -10/0/10(°C)
Main Results			
1-Cooling performance and COP: 5.7 kW and 2.1 respectively (at 6000 rpm)			
2-Heat Pump heating performance and COP: 5.9 kw and 1.9 respectively (at 10°C)			
3-Heat Pump heating system consuming less energy than PTC system (at 0°C)			
4-Heat Pump heating system is insufficient for heating the cabin (at -10°C)			
5-At low outside temperature, heat pump heating system and PTC heating system should be work simultaneously to provide heating the cabin			

the internal heat exchanger profiles were optimized the design parameters for R-1234yf. An optimized profile was obtained by considering minimized liquid volume and suction pressure drop, maximized heat transfer and limited liquid pressure drop (Seybold *et al.* 2010).

The recent studies available in the literature and the main results of these studies are listed in Table 1.

3. Performance tests of the heat pump systems for electric vehicles

In this section, performance tests were reviewed for AHP air conditioning systems for electric vehicles in available literature and the recent researches are listed in Table 2.

3.1 Heat source

As mentioned above using ambient air as an only heat source cannot be satisfied the desired conditions to heat the cabin of the vehicle sufficiently. Additional heat sources such as heat collection from batteries, driven electric motor and its power control unit etc have to be needed. At low ambient air temperatures (-10°C), heating requirement of the vehicle can be obtained by the heat pump system. In a research, improved heat pump system used a secondary evaporator in the cooling circuit of the electrical driven device was used to recover efficiently wasted calories and the cooling circuit was a liquid type circuit (i.e. mixture of water and glycol) that presents the advantage of a higher efficiency compared with an air type cooling circuit. The average heating power delivered by the heat pump could be about 2 kW at an ambient temperature of -10°C for a mean compressor electrical consumption of 1.15 kW and a calorific power recovered from the batteries of about 0.5 kW (Pomme 1997).

In another research, the effects of air source and waste heat source from electric devices on a heat pump system was investigated experimentally. Performance of the heat pump system was evaluated by varying the mass flow rate. The results of study showed that the heating capacity and COP in the dual heat source heat pump were increased by 20.9% and 8.6%, respectively, from those of the air-source heat pump (Woo *et al.* 2013). Heat pump systems can be improved with the other technologies such as AHP systems using with different heat sources which are ambient air, engine coolant and exhaust gas (Direk *et al.* 2011). Air source AHP system which used ambient air was investigated to performance evaluation for steady state conditions. The experimental setup can be shown in Fig. 4. From the results of this study, air source AHP can supply additional energy for energy efficient vehicles which had no waste heat and experimental data showed that air to air AHP system working with R-134a provides acceptable heating capacity for mild weather conditions. Another result from the study was about COP and can be shown in Fig. 5. According to Fig. 5, COP was decreased with increasing compressor speed both of cooling and heating modes (Hosoz and Direk 2006).

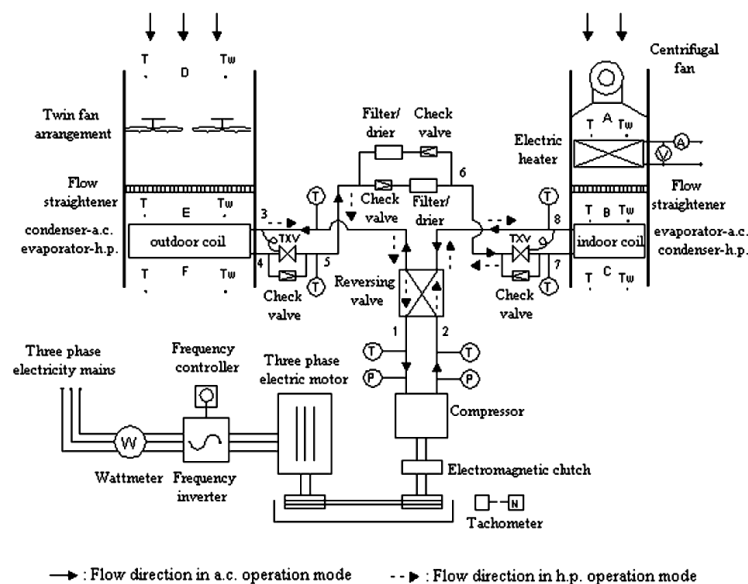


Fig. 4 Schematic view of the experimental automotive air conditioning/heat pump system (Hosoz and Direk 2006)

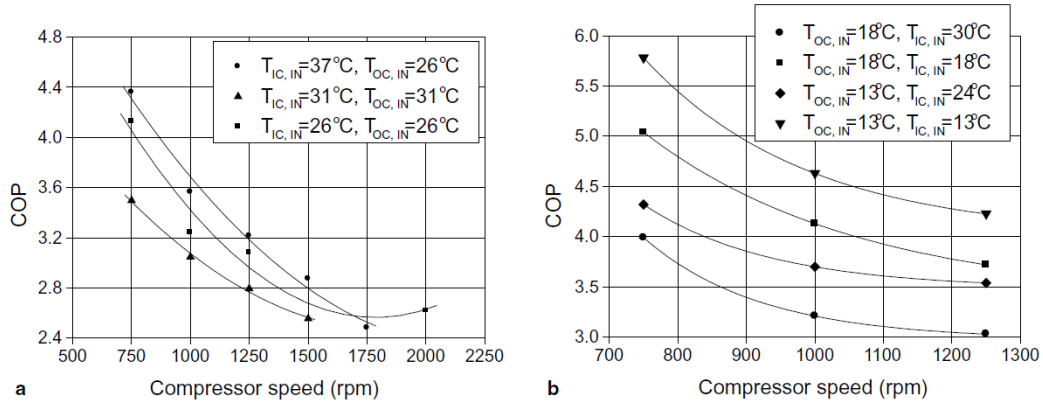


Fig. 5 Variations in the COP with compressor speed for the cooling mode (a) and heating mode (b) (Hosoz and Direk 2006)

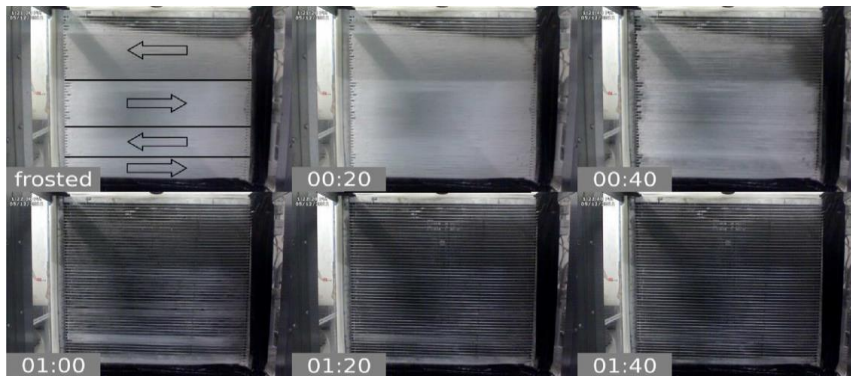


Fig. 6 Exterior heat exchanger during reverse cycle defrosting (time [mm:ss]) (Steiner and Rieberer 2013)

On the other hand, heat pump system working on heating mode, the outdoor heat exchanger is used as an evaporator but, at particularly low ambient temperature, the fin surfaces of the evaporator can be freeze and this cause to a decrease in the performances of the heat exchanger. The exterior heat exchanger reduced the performance because of defrosting shown in Fig. 6. The authors tested and simulated under different operation conditions and submitted solutions on the paper. The schematic view of the reversible cooling and heating system can be shown in Fig. 7 (Steiner and Rieberer 2013). Therefore, efficient methods have to be considered under severe weather conditions. For this purpose, an AHP system using refrigerant CO₂ was investigated by using simulation model. The model results showed that opening range of expansion valve have to be optimized considering defrost time and the system efficiency (Steiner and Rieberer 2015).

The heating performance of a dual source electric vehicle AHP system was investigated for the comparison of three different operation modes: air source-only, waste heat-only and dual source. The obtained experimental data revealed that at low outdoor air temperature dual source heating performance is better than the others. In this study each operation carried out at 0°C outdoor temperature and waste heat rate was 1.5 kW. The suction and discharge pressure values were obtained higher than the other ones for dual source operation mode as shown in Fig. 8, and the increased suction pressure led to an increment in mass flow rate of refrigerant (Ahn *et al.* 2014).

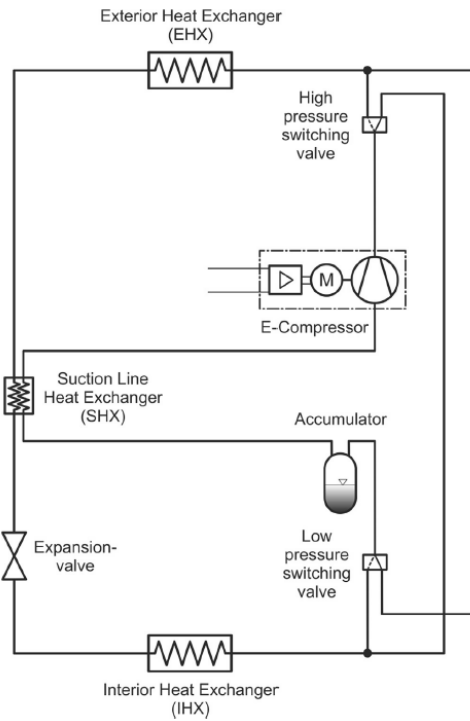


Fig. 7 Schematic view of the reversible heating and cooling system (Steiner and Rieberer 2013)

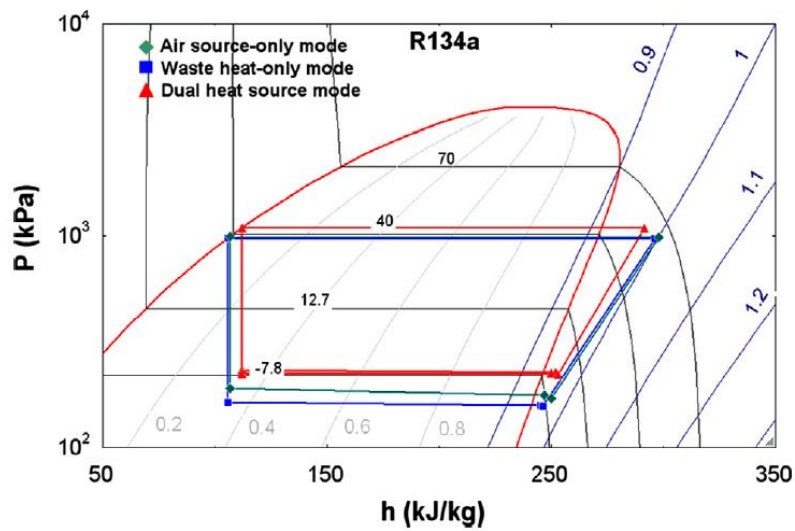


Fig. 8 Pressure-Enthalpy diagrams for different heat pump cycles (Ahn *et al.* 2014)

3.2 System design

Thermoelectric elements can work together the AHP systems under cold weather conditions. These systems can be named as hybrid AHP systems. Hybrid heating system composed of air

source heat pump and electric heater is more efficient than only using electric heater (Lee *et al.* 2015).

In some automotive applications with alternative fuel sources, such as fuel cell or direct injection diesel engines, the obtained heat from the engine is insufficient to warm up the cabin of the vehicle in winter conditions. A dual-loop cooling and heating system, which can work in both cooling and heating mode may overcome the problem mentioned above. In air conditioning mode, COP of the dual-loop system varied from 0.9 to 1.8 and for heat pump mode it varied from 2 to 5 depending on the ambient air conditions. There were some advantages of this system; adequate thermal energy was supplied to warm the cabin, the system was more compact and had less components, the system was also a solution to delayed heating problem. There were also some disadvantages; the system increases the emissions and fuel consumption (Jokar *et al.* 2005).

In the cooling process, amount of refrigerant charge was larger than the heating process and the heating capacity cannot satisfy the increasing heating demand at the lower ambient temperature for that reason a secondary heater can be added to the heat pump system in this experimental study (Feng and Hrnjak 2016). Different type of vehicles such as electric buses were also investigated and authors focused on electric bus heat pump system with using waste heat obtained from electric devices and air-source for cooling operation mode. From the experimental results, the transient air warm-up speed of the heat pump for a heating could be sufficiently used as the cabin heater for an electric bus which suffers from a short driving range (Lee *et al.* 2013).

The performance characteristics of a dual-evaporator heat pump system for dehumidifying and heating in electric vehicles were investigated. In this study, a heat pump (HP) and a dual-evaporator heat pump (DHP) combined with a heater were evaluated as an effective dehumidifying and heating units using waste heat recovery from the dehumidifying process. As a result of this study, HP and DHP systems had better performance than conventional AC system in the dehumidifying and heating operation (Ahn *et al.* 2015). The effects of the heat exchanger geometry on the heat pump system of electric vehicle were investigated. The authors used four kinds heat exchanger and found that small diameter heat exchangers used in heat pump of electric vehicles have a better application potential compared to the other ones (Yan *et al.* 2014).

3.3 Compressor types

The experimental studies include performance characteristics of the components of the AHP system were also investigated to improve and to get better performance range for different environmental conditions. Ambient temperature and compressor speeds on the system performance of electric vehicle AHP system was performed for different compressor types. In this study, three different compressor type named as swash plate variable displacement compressor, the scroll compressor and the electric scroll compressor which is the most common used in electric vehicles were used. The experimental results showed that swash plate variable compressor had the highest average cabin temperatures under the same conditions when the ambient temperature below -10°C and compressor speed 3400 rpm, the comparative results were shown in Fig. 9. But scroll type AHP system provided high cabin air temperature values when the ambient temperature was above -5°C (Wei *et al.* 2014).

Effect of variable capacity compressor on the automotive air conditioning system was investigated with a simulation model and an experimental bench. The experimental bench had original components from the air conditioning system of a vehicle. The simulation model included a variable capacity compressor, a thermostatic expansion valve, evaporator and micro channel

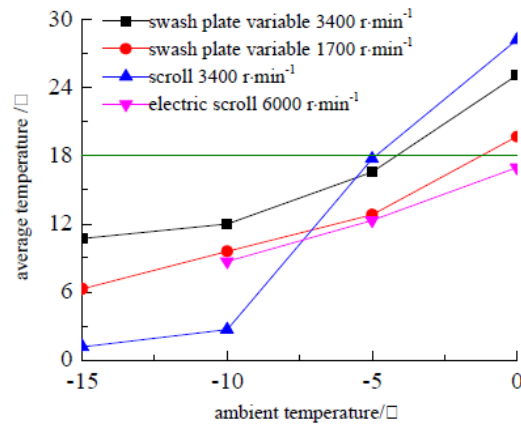


Fig. 9 Variations of the temperature difference of refrigerant between the inlet and outlet of the internal heat exchanger and the ambient temperature (Wei *et al.* 2014)

parallel flow condenser. The compressor was run by an electric motor. Effects of compressor speed had been experimentally evaluated and the system was simulated by means of developed model. According to results of the study, variable parameters such as the condensing air temperature and compressor speed did not affect the refrigerating capacity. On the other hand, the refrigerant capacity was affected by the evaporator return air temperature. Refrigerating capacity, mass flow rate and COP vary linearly with condensing and return air temperatures and compressor speed (Jabardo *et al.* 2002).

3.4 Fan control

Air conditioners have variable-speed compressors and variable expansion valve openings with feedback control to provide an improvement in performance and power efficiently. Fan control is another parameter of air conditioning system about energy usage and transient response. In a research, two control algorithms were used to incorporate the outdoor and indoor fan. The purpose of the first algorithm was reducing the steady state power consumption with changing outdoor fan speed. The second one modulated the indoor fan speed and improved the transient response. The control algorithm was also validated experimentally (Yeh *et al.* 2009).

The recent studies available in the literature about performance tests are listed in Table 2.

4. Thermal management of electric vehicles

4.1 System modeling and analysis

In electric vehicles, a great amount of energy consumption is needed for HVAC system and this energy is variable for different driving conditions. The recent studies available in the literature about thermal management of electric vehicles are listed Table 3. Management of the energy requirements of the HVAC system is very crucial for electric vehicles due to battery life and maximum driving range. For this reason, fully integrated vehicle model was developed for investigate energy management algorithms (Shojaei *et al.* 2015). Determining the thermal

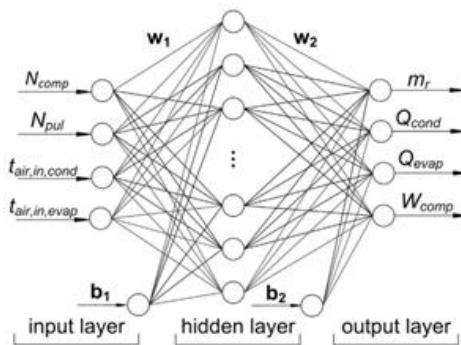
Table 2 Researches about performance tests available in the literature

Authors	Published Year	Refrigerants	System Components	Test Conditions
M. Hoşöz M. Direk	2006	R-134a	Heat pump system	Compressor speed: 750-2000 (rpm) Air dry bulb temperature: 26/31/37 (°C)
Main Results				
1-Heat pump system can provide the cabin heating requirement at mild weather conditions but at severe weather conditions the system is insufficient				
2-Both heating and cooling capacities increase with compressor speed process				
A. Steiner R. Rieberer	2013	CO ₂	Heat pump system	Air temperature: 0°C Relative humidity: 80%
Main Results				
1-Frost formation on the exterior heat exchanger reduces the performance and efficiency of the system				
2-Throttle valve openings on the defrosting process influence defrosting efficiency and defrost time				
M. Wei F. PENG H. Huang Z. WANG P. Song H. Zhang	2014	R-134a	Heat pump system	Compressor speed: 1700/3400/6000 (rpm) Ambient temperature: -15/-10/-5/0(°C)
Main Results				
1-At ambient temperature range of -15 to -10°C and at the same compressor speed (3400 rpm) swash plate variable displacement compressor has higher cabin average temperature than scroll compressor				
2-The above situation is also valid between -10 and -5°C but approaching to -5°C, the situation is reversing. At ambient temperature range of -5 to 0°C scroll compressor has higher cabin average temperature swash plate variable displacement compressor				
3-To making a comparison in swash plate variable displacement compressor, average temperature in the cabin increases with the speeds of compressor				
J. H. Ahn H. Kang H. S. Lee H. W. Jung C. Baek Y. Kim	2014	R-134a	Four types of small diameter tube Fin heat exchanger	Operation modes: Air source-only Waste heaty-only Dual heat source
Main Results				
1-In the air source-only mode, COP and heating capacity increased with increasing outdoor air velocity and outdoor air temperature				
2-In the waste heat-only mode, COP and heating capacity increased with increasing waste heat amount				
3-In the dual heat source mode, COP and heating capacity increased with increasing waste heat amount and outdoor air temperature				
4-The heating performance in the dual heat source mode was higher than the other modes				
R. Yan Jun-ye Shi H. Qing J. Chen	2014	R-134a	Dual source heat pump system	Compressor speed: 2000/3000/4000 rpm Temperature out of the chamber: 7°C Temperature in the chamber: 20°C
Main Results				
1-The small diameter tube and fin heat exchanger can exceed the microchannel heat exchanger on heating capacity and COP				
2-The capacity of microchannel heat exchanger decreases after several frost/defrost periods				
3-Small diameter tube and fin heat exchanger have good potential for electric vehicle heat pump systems				

Table 2 Continued

H. Lee	J. Won	2015	-	Air-sourced heat pump system	Compressor speed: 2000/3500 (rpm) Ambient temperature: -10/5 (°C)
C. Cho	T. Lim				
H. Jeon	E. Lee				
S. Oh	Y. Kim				
Main Results					
1-At 3500 rpm compressor speed and -10°C ambient temperature, to reach the comfort level need more heat capacity in the system					
2-The system air-sourced heat pump and electric heater work together is more efficient than only electric heater					

management strategy, there are several parameters include such as performance, functionality, volume, mass, cost, maintenance, safety etc. There are also different system types of thermal management such as active/passive cooling, liquid cooling, air cooling, cooling-heating system, only cooling systems etc. Apart from these parameters, location of the battery pack has an important role on the battery thermal management (Pesaran 2001). Thermal behavior of the batteries of electric vehicles and mathematical models were also investigated considering thermal management system. PCM material is a better selection than the others for the battery thermal management system and these materials need to be investigated experimentally considering the possibility of the heat collection and recycling needs in terms of energy saving efficiently. (Rao and Wang 2011). Artificial neural network model and MATLAB-SIMULINK were also used by researchers to predict the performance of electric vehicle air conditioning system based on the experimental data in general (Tian *et al.* 2015, Kiss *et al.* 2015). Artificial neural network model for the performance prediction of electric vehicle air conditioning system was illustrated in Fig. 10.

Fig. 10 A model for performance prediction of Electric Vehicles Air Conditioning System (Tian *et al.* 2015)

The model input parameters are the compressor speed (N_{comp}), electronic expansive valve opening (N_{pul}), condenser inlet temperature ($t_{air,in,cond}$), evaporator inlet temperature ($t_{air,in,evap}$), while the refrigerant mass flow rate (m_r), heat rejection of condenser (Q_{cond}), refrigeration capacity (Q_{evap}), and energy consumption of compressor (W_{comp}) are the output parameters. Detailed information about this model can be found in reference (Tian *et al.* 2015).

HVAC energy consumption of plug-in electric vehicles was investigated for different geographical zones (Kambly and Bradley 2014). As it has been mentioned before, waste heat of electric vehicles is much lesser than internal combustion engine vehicles and for this reason waste heat thermal management system in the electric vehicles is another important issue. Energy consumption of electric vehicles which utilize waste heat and three different heat sources for HVAC energy is shown in Fig. 11 (Park 2015). Pre-heating system had a great effect on reduction of energy consumption than the other when the vehicle is running.

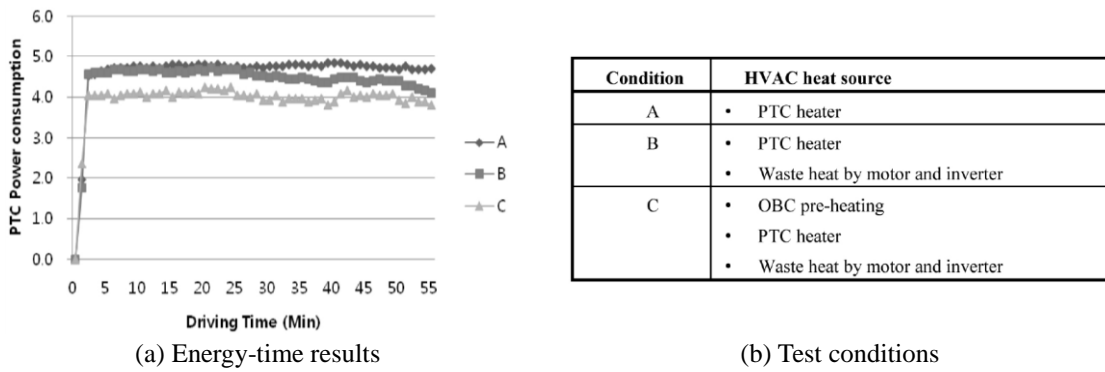


Fig. 11 Experimental results and test conditions (Park 2015)

A thermal management system called Thermal Link System which is shown in Fig. 12 was developed and this system composed of heat-pump air conditioner, a system recovering waste heat from the electric power train and a heat exchanger located between the refrigerant and coolant water of power train. The main results of this study were that i) the temperatures of separated water cycles can be controlled independently ii) due to heat pump air conditioner and waste heat recovery, energy consumption can be reduced iii) the system can set the device cooling water temperature below that of the surrounding air (Yokoyama *et al.* 2011).

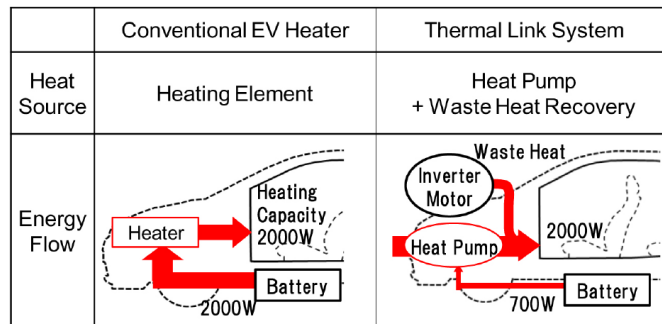


Fig. 12 Schematic diagram of conventional and developed system (Yokoyama *et al.* 2011)

A tool for design, analyze and optimization of an air conditioning system for an electric minibus was developed and this system consist of dynamic models of each component of the

system such as fans, compressor etc. Simulation of the overall performance of the vehicle was achieved in MATLAB-SIMULINK software. The validated model can be estimated of effects of different parameters on the overall performance (Torregrosa *et al.* 2013).

On the other hand, different strategies were developed for during cooling period by using the vehicle thermal model such as zonal cooling shown in Fig. 13. The most effective solution was proposed as a combined configuration includes reduction of thermal loads and zonal cooling strategies (Jeffers *et al.* 2015).

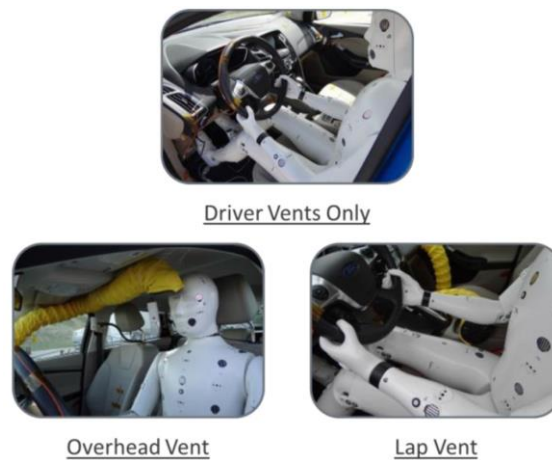


Fig. 13 Zonal cooling test configurations (Jeffers *et al.* 2015)

In order to manage and improve the whole system performance conducted with CFD and experimental results, 1D analysis methods can be utilized. A system simulation by using AMESIM to represent the subsystems such as air conditioning system, cabin models and electric loads of electric vehicles etc. was investigated and the 1D model developed in this study is shown in Fig. 14. This model can quickly estimate with changing subsystem parameters such as refrigerants, cooling and heating insulation etc. (Vijay 2012).

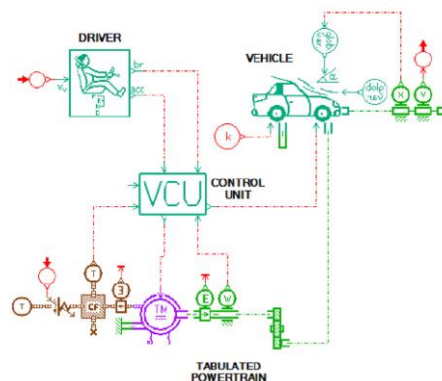


Fig. 14 Model of vehicle combined with powertrain of the electric vehicle (Vijay 2012)

In the literature, there are also dynamic system simulations, by using MATLAB-SIMULINK, based on thermal comfort parameters: interior air temperatures, humidity, mean radiant temperature and air velocities (Kılıç and Akyol 2009). Additionally, the dynamic model was improved with view factors obtained from CFD analyses. The model had also included the effects of car color, windows optical properties and physiological reactions of driver (Akyol and Kilic 2010). The comparative results with experimental data are shown in Fig. 15.

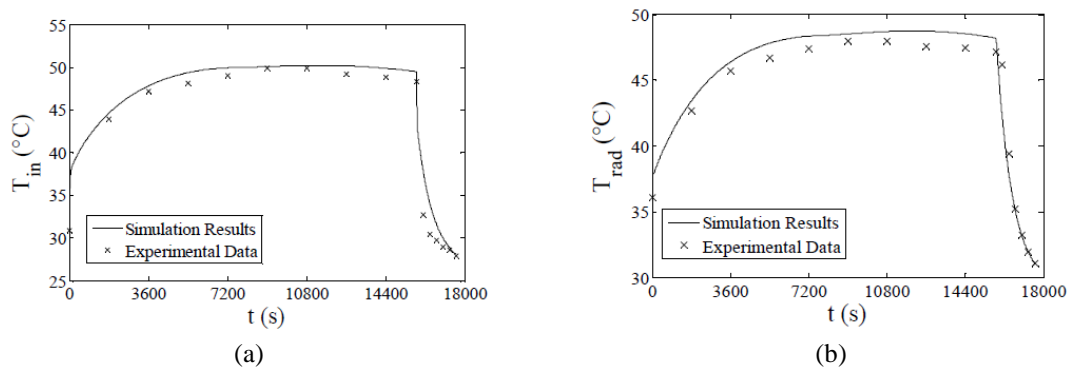


Fig. 15 Comparison measured and calculated values of, (a) interior air temperature (b) MRT(Mean Radiant Temperature) (Akyol and Kilic 2010)

A Combined Fluid Loop (CFL) thermal management system of electric vehicle based on heat pump system is shown in Fig. 16 and this system was developed for improving electric drive vehicle range. The aim of this loop is to enhance the range of electric vehicles and reduce thermal system weight and volume. This technology combines the cabin energy storage systems with power electronics and electric motor components. The author developed this model so that the separate cooling systems of current vehicles have additional heat exchangers which has disadvantage in view of weight and driving range. The author found that using the CFL system also enables hot or cold coolant to be directed to the passenger cabin, this led to air conditioner or heat-pump without reversing the refrigeration cycle (Leighton 2015).

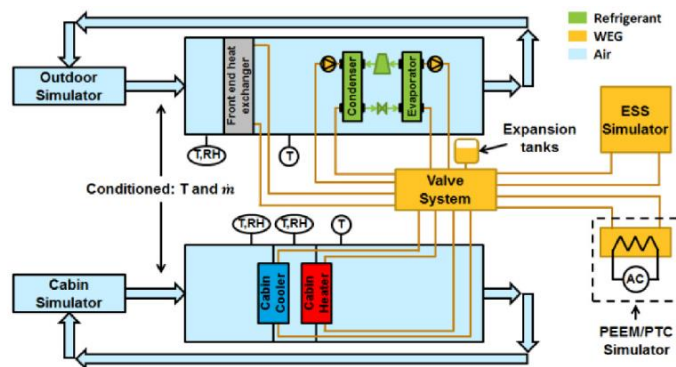


Fig. 16 Schematic view of CFL test system using in reference (Leighton 2015)

Apart from all of these thermal management methods, thermal management of batteries has a crucial role not only for electric motors but also electric car HVAC systems and the cooling methods for the batteries are classified in Fig. 17 (Pan *et al.* 2016). The improvements and enhancements can be achieved by considering more efficient cooling methods of battery systems and also an efficient recovery of battery cooling systems.

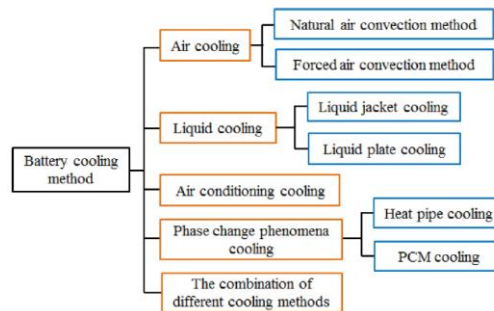


Fig. 17 Classification of the battery cooling methods (Pan *et al.* 2016)

4.2 Computational fluid dynamics analysis

On the other hand, a HVAC system based on conventional or heat pump system could not only satisfy the heating, cooling and defrosting/dehumidifying processes but also provide desired conditions considering thermal comfort and driver and passenger's safety. Therefore, it is necessary to understand the thermal characteristics of the human body to design an effective HVAC system (Kaynakli *et al.* 2005). The managing of thermal comfort in vehicles has also great effect on the energy consumption of the electric vehicle air conditioning system. An occupied zone HVAC system which consumed HVAC energy efficiently was proposed and developed (Kwon *et al.* 2012). In this system, an occupied-zone (OC) HVAC system was proposed to increase the range of an electric vehicle. There were three zones, driver, passenger and rear seating positions shown in Fig. 18 and each zone air temperature and air flow rate was controlled independently while conventional HVAC system air conditions affects entire the vehicle cabin. According to tests and Computational Fluid Dynamics (CFD) analysis, the proposed system was reduced power consumption by 17% for cooling and 20% for heating modes.

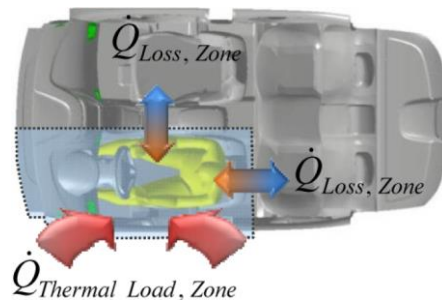


Fig. 18 Heat transfer path for driver (Kwon *et al.* 2012)

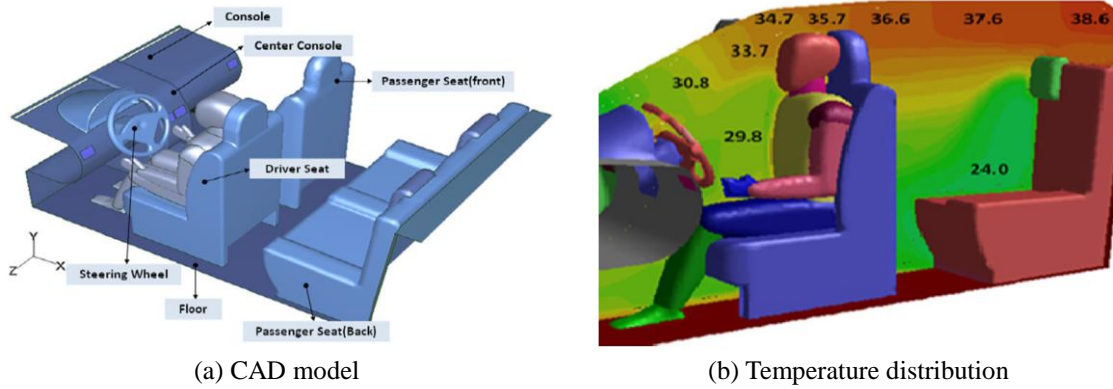


Fig. 19 CAD model of the vehicle cabin in using CFD calculations and temperature distributions of middle plane of the vehicle (Kilic and Sevilgen 2012)

Whole body									Whole body								
t (s)	q_c (W/m ²)	h_c (W/m ² K)	T_c (°C)	ϕ_c	q_r (W/m ²)	h_r (W/m ² K)	T_r (°C)	ϕ_r	t (s)	q_c (W/m ²)	h_c (W/m ² K)	ϕ_c	q_r (W/m ²)	q_r (W/m ²)	h_r (W/m ² K)	T_r (°C)	ϕ_r
60	32.2	17.9	20.4	0.54	27.8	5.5	15.3	0.46	60	90.4	12.4	0.62	146.8	56.4	5.7	15.8	0.38
180	30.8	14.9	21.5	0.51	29.2	5.5	16.2	0.49	180	78.1	11.3	0.60	131.2	53.0	5.8	16.4	0.40
300	30.1	13.0	22.4	0.50	29.9	5.6	17.0	0.50	300	70.1	10.3	0.58	120.2	50.1	5.8	16.9	0.42
600	27.5	8.1	25.3	0.46	32.5	5.7	19.6	0.54	600	51.3	8.0	0.54	94.6	43.2	5.9	18.2	0.46
900	26.5	6.6	27.1	0.44	33.5	5.8	21.4	0.56	900	39.4	6.4	0.51	77.3	37.8	5.9	19.2	0.49
1,200	26.5	5.2	27.9	0.44	33.5	5.9	22.2	0.56	1200	36.3	5.9	0.51	71.8	35.5	5.9	19.6	0.49
1,800	26.6	5.7	28.7	0.44	33.4	5.9	23.1	0.56	1800	32.0	5.2	0.49	64.8	32.7	6.0	20.1	0.51

(a) Constant heat flux boundary condition on the body (b) Constant temperatures boundary condition on the body

Fig. 20 Heat transfer characteristics of the whole body for 30 minutes of heating period (Kilic and Sevilgen 2009)

Three-dimensional transient numerical analysis is now a common tool to evaluate the desired conditions in vehicle cabin considering thermal comfort conditions. The effects of using different type of inlet vents on the thermal characteristics of the automobile cabin and the human body during cooling period was investigated and the main results of this study was that the different velocity and temperature distributions can be obtained by selecting different type of inlet vents for cooling period without changing HVAC cooling load. The numerical results of temperature distribution of this study are shown in Fig. 19 (Kilic and Sevilgen 2012). Numerical CFD investigation of an automobile cabin during heating period and comparison of the results to the experimental data was performed in a transient condition and the authors emphasized that the local heat transfer characteristics of the human body has significant importance to design an effective HVAC system. Another important result of this study was that both constant heat flux and constant temperature boundary conditions could be applied to the manikin surfaces during transient numerical simulations for the vehicle cabin. Predicted heat transfer characteristics of the whole body for 30 minutes of heating period are shown in Fig. 20 (Kilic and Sevilgen 2009).

5. Conclusions

In this paper, a detailed literature review is performed. While reviewing the available published extensive studies, we focus on automotive heat pump systems of electric vehicles in view of

Table 3 Researches about thermal management available in the literature

Authors	Published Year	System Components	Test Parameter/Conditions
A. Yokoyama T. Osaka Y. Imanishi S. Sekiya	2011	Heat-pump air conditioner A system recovering waste heat A heat exchanger between the air-conditioner refrigerant and the power-train coolant water	Compressor speed: 2000-5000 (rpm)
Main Results			
1-In order to obtain 2000 W heating capacity, the power consumption target of the Thermal Link System is less than 700 W which is one third of the power consumption of a conventional heater			
2-Due to heat pump air conditioner and waste heat recovery system working together, the heating energy consumption can be reduced to below 580 W for 2000 W heating capacity			
C. Kwon C. W. Lee L. Foster J. Kwon Y. Shin	2012	Occupied-Zone (OZ) HVAC system	Ambient temperature: 0-35 (°C) Sun load: 0-850 (W/m ²)
Main Results			
1-For the driver-selected zone, cruising range of the vehicle was increased by 4% and 9% for cooling and heating, respectively			
2-For the driver-selected zone, HVAC power consumption was reduced by 17% and 20% for cooling and heating, respectively			
Hari Vijay	2012	PTC heaters R-134a refrigerant loop Simulation subsystems: Electric loads Batteries Air conditioning system Electronics Cabin models	Ambient temperature: -5//35 (°C) Solar flux: 0//1000 (W/m ²) Cabin requested temperature: 20 (°C)
Main Results			
1-The numerical model presented the estimation of the energy consumption of the electric vehicle and temperature of the cabin			
2-The numerical model can estimate the energy consumption and temperature of the cabin when the properties such as drive cycles, refrigerants, other heating-cooling technologies like heat pumps change			
B. Torregrosa-Jaime J. Payá J. Corberan	2013	Auxiliaries Heat pump	No solar loads Compressor speed: 2000-7000 (rpm)
Main Results			
1-Electric auxiliaries such as the fans and blowers consume a significant amount of the total energy consumption			
2-The control strategies have to be optimized for minimum energy consumption			
Z. Tian Ch. Qian B. Gu L. Yang F. Liu	2015	Electric vehicle air conditioning system (EVACS)	Scroll compressor speeds Electronic expansion valve (EEV) openings Ambient temperatures

Table 3 Continued

Main Results			
1-Mean relative errors in the established ANN were 1.87% for refrigerant mass flow rate, 2.71% for condenser heat rejection, 1.79% for refrigeration capacity and 1.64% for compressor power consumption			
2-According to the statistics values, Artificial Neural Network (ANN) with suitable configuration could be a reliable approach for EVACS performance prediction			
3-ANN model can aid to application engineers to determine performance of EVACS without requiring exhaustive experiments			
T. Kiss J. Lustbader D. Leighton	2015	Combined fluid loop (CFL) thermal management system	Ambient temperature of CFL system: -2//43 (°C)
Main Results			
1-The simulation and experimental data are in a good agreement within 5%			
2-The validated system model can estimate locations for the power electronics and electric motor to obtain quick cabin heating starting from cold soak			
H. S. Park	2015	PTC heater On-board charger (OBC) pre-heating Waste heat by motor and inverter	Outdoor temperature: 0 (°C) Target temperature: 32 (°C)
Main Results			
1-PTC heater energy consumption is reduced when waste heat management system enable			
2-Pre-heating system has greater effect on reduction of energy consumption			
Daniel Leighton	2015	Combined fluid loop (CFL) thermal management system	Ambient temperature: -12//43 (°C)
Main Results			
1-Power electronics and electric motor (PEEM) waste heat recovery increased range by 2% at both mild and extreme cold weather conditions			
2-Non-optimized CFL system showed an electric vehicle range increase 9%			

refrigerants, performance tests and thermal management of these systems. The main results of this study are described considering refrigerants, system performance and thermal management.

According to this study, the main conclusions considering current and alternative refrigerants are listed below.

- AHP systems using different refrigerants have its unique advantages and disadvantages in terms of driving conditions, outdoor ambient temperature and battery life, etc. Due to having better thermal properties, R-744 is an alternative refrigerant to R-134a, but developing more efficient optimization and control algorithms for thermal management of electric vehicles can be an advantage of using R-134a heat pump system.

- The experimental studies include alternative refrigerants such as R-152a, R-161, R-1234yf, and hydrocarbon mixtures were performed under different conditions due to global warming and legal regulations for emissions, heat pump technology with refrigerant R-1234yf is a satisfying choice for the both electric and conventional vehicles. But the application of CO₂ heat pump technology is a very attracting method and these systems may be choice for the next generation electric vehicles depends on the future developments in the industry.

- R-1234yf preferring to R-134a because of environmental properties such as low GWP, not required too much modifications for converting system from R-134a to R-1234yf.

- R-1234yf can be used as a long term environmentally friendly solution in mobile air conditioning systems due to its environmentally properties with acceptable performance.

The main conclusions in view of system performance of electric vehicles are described below.

- In the electric vehicle's climate control system, a hybrid heat pump HVAC system seems a more sustainable technology compared to the others such as PTC heaters etc.

- Fan control is an important parameter of air conditioning system about energy usage and transient response.

- The AHP performance can be improved with designing more efficient heat exchangers, especially for outdoor environment, in cold weather conditions.

- Air source AHP system which used ambient air working with R-134a provides acceptable heating capacity for mild weather conditions.

- In heat pump systems the exterior heat exchanger must be avoid to freezing.

- Some added modification to the heat pump can significantly increase the heating capacity and COP such as gas injection.

The main conclusions about thermal management of electric vehicles are proposed below.

- In the thermal management of electric vehicles, full integrated control algorithms which include not only electric vehicle system but also cabin interior thermal comfort models integrated with main control systems can be developed and reduce the energy consumption of vehicles.

- Dynamic simulation models of the subsystems as well as the entire systems can enhance the performance and estimate the different parameters effects.

- Local control zones defined in vehicle cabin interior may improve the management of the thermal systems of electric vehicle and reducing the energy consumption.

- CFL system can improve the range of electric vehicles and reduce thermal system weight and volume.

- Numerical methods such as CFD can be used for improving not only thermal comfort conditions but also thermal management of electric vehicles.

- The improvements and enhancements can be achieved by considering more efficient cooling methods of battery systems and also an efficient recovery of battery cooling systems of electric vehicles.

- PCM material is a better selection than the others for the battery thermal management system and these materials need to be investigated experimentally in a more detailed results considering the possibility of the heat collection and recycling needs in terms of energy saving and efficient.

As another result of this study, we can recommend that much research will be worked about these subjects to achieve better understanding and improving the thermal management and energy efficiency of electric vehicles.

Note

This paper is revised and expanded version of a paper entitled "Advances on heat pump applications for electric vehicles" presented at OTEKON2016, 8. Automotive Technologies Congress, Bursa, 23-24 May, 2016.

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