



## Review article

Recent advances on air heating system of cabin for pure electric vehicles:  
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## ABSTRACT

Due to the environmental protection and energy shortage, the electric vehicles (EV) is gradually replacing traditional fuel vehicles. EV generally use more energy for air conditioning system, especially EV have almost no waste heat from engine to be discharged to the passenger compartment to achieve thermal comfort in heating condition. The energy consumption of the heating system for EV will decrease the maximum mileage. Therefore, the energy saving technology for heating system is developing and applied for EV. The article introduced the advance of conventional and emerging heating system for the EV. The positive temperature coefficient (PTC) heater is a convenient heating method used in EV, but PTC heater has some defects such as low efficiency. The heat pump (HP) system is gradually replacing PTC. However, HP has various problems to be overcome, such as the heating capacity and efficiency in low temperature environment. In addition, other novel technologies are proposed to reduce the energy consumption. This article reviews the literature of novel heating methods for EV, introduces adsorption air conditioning systems (AAC), fuel combustion (FC), heat storage (HS), waste heat recovery (WHR), thermoelectric effect (TE) and magnetocaloric effect (ME).

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## 1. Introduction

At present, many environmental problems are emerging, and problems such as global warming and resource scarcity are issues that we need to face together. Automobile energy consumption accounts for a large proportion of total oil energy consumption, and has been reached more than 30% in the past few years [1]. Due to the shortage of oil and the pollution of oil on the environment, the United Nations and countries around the world have planned to restrict the production and use of fuel vehicles to achieve sustainable development goals. China has also proposed a project to increase the proportion of new energy and clean energy-powered vehicles to about 40% by 2030. In order to achieve the goal of low carbon and pollution-free, many companies are currently developing products that are more environment-friendly and consume less energy, EV is one of them. Unlike traditional cars, EV have almost no waste heat that needs to be discharged to the passenger compartment to

achieve thermal comfort in the cabin. When the heating system of the EV is turned on, the maximum mileage of the EV will be affected. Therefore, how to obtain an efficient and energy-saving EV heating system and improve the vehicle's mileage has become a difficult problem.

In this regard, many previous studies have discussed different heating technologies for EVs from different perspectives. Several articles compare many technologies and discuss their advantages and disadvantages. In 2016, Peng et al. [2] introduced the application of environmentally friendly refrigerants in EVs, and reviewed systems such as multi-source HPs, but the advantages and disadvantages of different HP systems were not compared in the article. In 2018, Zhang et al. [3] reviewed the mileage extension strategy of EVs, but his paper did not mention more novel heating methods to achieve the purpose of making EVs more energy-efficient and improving their range. This paper continues the efforts of previous researchers by comprehensively reviewing

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different alternative heating techniques and comparing the advantages and disadvantages of different approach techniques.

PTC heating as one of the options has been widely used in commercial EV, but due to its relatively low energy efficiency, it consumes a lot of electricity and sometimes leads to a lack of power [4]. As an alternative, the automotive industry has introduced an ASHP system. ASHP is an excellent method to save energy while meeting climate control requirements [5], it is energy-saving and has both cooling and heating capabilities. However, when the ambient temperature is extremely low, the flow of refrigerant in the ASHP system will be reduced, resulting in poor ASHP system performance [6]. Therefore, it is necessary to improve the efficiency of the ASHP system under low temperature environmental conditions.

The existence of the adsorption air conditioning (AC) system is helpful to solve the problems of heavy heating burden and short battery life of EVs, and also helps to reduce the energy consumption in the heating process. The proposal of the fuel burning system separates the heating system from the battery system, which also greatly saves vehicle mileage. The heat storage system can also achieve a similar purpose through heat storage. In addition, since about half of the energy in the exhaust emissions of EVs is lost in the form of heat, recycling the waste heat can also reduce fuel loss and improve the performance of the heating system. At the same time, the application of magnetocaloric effect and thermoelectric effect technology is booming, and may replace HP systems in the future.

This article introduces the heating systems that can be used in EV and reviews the heating methods of air heating and water heating PTC systems. Secondly, it analyzes the replacement of the refrigerant in the HP system, different options, especially the refrigerator injection systems and the secondary loop systems, and introduces the HP systems with dehumidification and defogging function and the HP systems with novel heat exchanger. This article introduces the principle of adsorption AC, summarized the system composition and application of the fuel combustion system. The application of energy storage heating and different devices are introduced, and the advantages and disadvantages of the waste heat recovery systems and solutions are analyzed. Finally, the emerging technologies such as the application of magnetocaloric and thermoelectric effect in EV heating are summarized.

## 2. PTC heating systems

In the heating ventilation and air conditioning (HVAC) system of EVs, EVs cannot use the waste heat generated by the engines of fuel-fueled vehicles for heating, many car manufacturers use special heating devices to achieve heating. PTC thermistor is a typical semiconductor resistor with a positive temperature coefficient, and it is one of the most used heating methods in electric air conditioners [7].

PTC heater has the advantages of low thermal resistance, high heat exchange efficiency and low power attenuation for long-term use [8]. There are air heating and water heating in the form of PTC heaters. These two options will be explained in the following sections.

### 2.1. Air heating

There are two types of air heating: high-voltage air heating and low-voltage air heating. Low-voltage air heating system adds water pumps, water pipes, three-way valves and heating cores, motors, and radiator water tanks to form a closed water circulation system. At the same time, low-voltage air heating heaters are added to the HVAC system. The system structure of the high-voltage air heating method removes the water inlet and outlet pipes and the heater core of the original car, and replaces the heater core with an air heating PTC of the same size and the same installation method as the car heater core, and then changes the related control circuit. Thermal insulation measures should be taken for the core [9]. During operation, the PTC heating device provides a heat

source to heat the water in the radiator water tank, and then the hot water enters the heater core to directly heat the air.

High-voltage air heating heaters can provide higher power output and efficiency heating than low-voltage air-heating heaters. At the same time, the method directly heats the air, which makes the car have a faster temperature rise rate. Park et al. [10] constructed a PTC air heating system with a closed-loop device as shown in Figure 1, analyzed the efficiency of the heater and adjusted the geometric variables. The efficiency of the system is as high as 98%, and the output density has been increased. To make the air conditioning and heating system meet the defrosting and defogging regulations and heating requirements, the heating power of the PTC needs to be at least 3 kW or more. This power is a huge consumer relative to the total battery capacity, which leads to a dramatic drop in the mileage of pure EVs.

### 2.2. Water heating

Compared with air heating, the water heating PTC system has a more compact structure, a lighter weight, and a higher heating efficiency. Bohlender and Reiss [11] has developed a PTC water heating system, the system contains of a continuous flow heater and an integrated high-pressure controller. The electronic water pump and the PTC heating system are integrated in the design. The design reduces the space size and weight of the system, and significantly improves the heating efficiency. Huang [12] also disclosed a new type of water PTC heater, which enhances heat transfer and improves safety. The equipment also solves the problem that the tube wall and the internal heating element cannot be closely attached, which reduces the heat transfer effect and affects the service life.

However, the electric power of the PTC heater for water heating is about 5.5 kW, which is a huge consumption relative to the total battery capacity. Due to the limitation of battery power, the PTC system will adversely affect the cruising range when it is running [13]. Reduce cruising range. In addition, the problem of poor cooling performance of PTC heaters also needs to be solved.

## 3. Vapor compression heat pump systems

Because the opening of the PTC heating system will greatly increase the fuel consumption of EVs, an efficient heating system for EV is required. As the most popular heating system at present, the vapor compression HP system can provide the same heating capacity as the PTC heater, and is more efficient and more economical. In the traditional HP system, the refrigerant is compressed by the compressor and flows to the heat exchanger in the EV. The high-pressure and high-temperature refrigerant releases a large amount of heat in the heat exchanger and flows to the condenser through the expansion valve. After absorbing external heat, the refrigerant returns to the compressor to realize circulation. However, there are many problems in the heat pump system, such as the urgent need to replace the refrigerant. We will summarize the solutions to different problems in the following sections.

### 3.1. Replacement of refrigerant

Due to the large GWP of R134a, the automotive industry is considering replacing R134a. At present, most car manufacturers are considering replacing the next refrigerant, but the choice is not clear. For EVs, the choice of refrigerant is very difficult, and the heating capacity and efficiency of the refrigerant should be considered when choosing.

As one of the constituent materials of the earth's biosphere, R744 is relatively friendly to the environment. As a natural refrigerant, it was first used as a refrigerant in 1866. Junqi et al. [14] studied the HP structure of R744 and tested its heating performance in different environments. The test results show that the heating efficiency of the R744 system in the heating mode (Figure 2) is better than that of the R134a. In addition, when R744 is used as a refrigerant, the system has strong

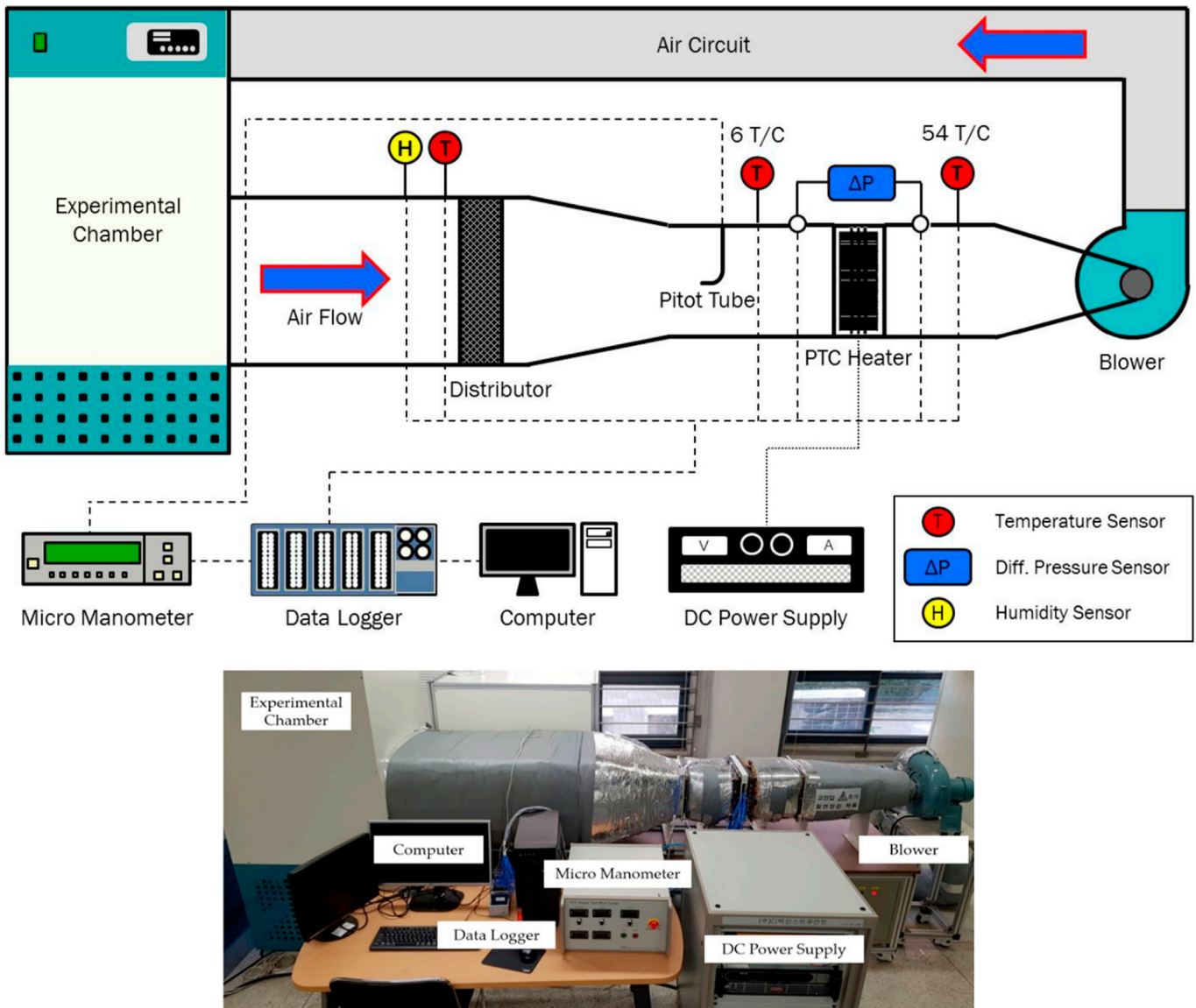


Figure 1. Schematic diagram and photo of the PTC heater experimental apparatus [10].

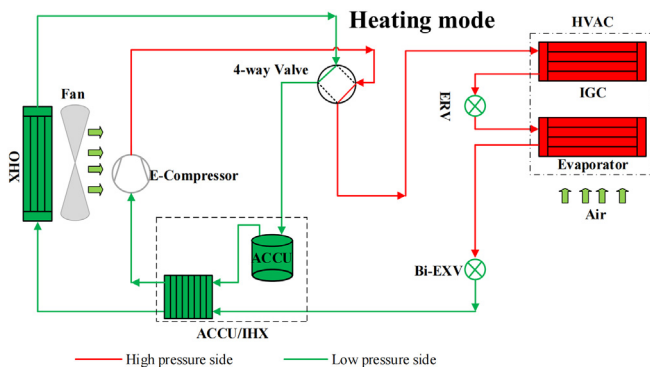


Figure 2. Schematic diagram of R744 HP system [14].

heating capacity and high COP in low temperature environments such as  $-20\text{ }^{\circ}\text{C}$  and  $-25\text{ }^{\circ}\text{C}$ . Under the same test conditions, Yibiao et al. [15] obtained the same conclusions. After testing the effects of experimental temperature and compressor speed on system performance, Song et al. [16] found that the HP system using R744 as a refrigerant in cold climates can provide satisfactory performance, a heating capacity of 15.3

kW and a COP of 1.78 can be achieved even under the conditions of  $-20\text{ }^{\circ}\text{C}/20\text{ }^{\circ}\text{C}$ . However, it should be noted that although the HP system using R744 refrigerant has good heating performance in a low temperature environment, its COP is low during cooling, especially in a high temperature environment.

As a natural hydrocarbon, R290 was used as a refrigerant in the early 20th century. R290 has excellent thermal performance, low price, and has no direct impact on the atmospheric environment. Liu et al. [16] proposed for the first time a technical solution for applying R290 to the mobile HP system of EVs. The research also compares different HP technology schemes, operating conditions are shown in Table 1. The comparison found that when the outdoor environment temperature is above  $-10\text{ }^{\circ}\text{C}$ , the heating capacity of the system is best when R290 is used as the refrigerant, and its performance in cooling is also very good.

R407C is an environmentally friendly refrigerant that does not destroy the ozone layer. It was proposed around 2000 and is a mixture of multiple refrigerants. Wang et al. [18] used R407C as a refrigerant to conduct heating tests in environmental test chambers, and developed a system. Tests show that when R407C is used as a refrigerant, the system's working capacity is improved, but the energy efficiency has been reduced and its COP value is moderate during cooling.

**Table 1.** Operation condition [17].

Heat pump strategy	Compressor speed (rpm)	Compressor displacement (cc)	Indoor air temperature (°C)	Outdoor air temperature (°C)
R134a without EVI	3000	27	20	0, -10
R1234yf without EVI	3000	27	20	0, -10
R134a with EVI	3000	27	20	0, -10, -20
CO <sub>2</sub>	3900	6	20	0, -10, -20
CO <sub>2</sub>	3900	6	-20	-20
R290	3000	33	20	0, -10, -20
R290	3000	33	-20	-20
R290	4000	33	20	-10, -20
R290	5000	33	20	-20
R290	6000	33	-20	-20

Because R1234yf is compatible with R134a components as a refrigerant, in 2009, R1234yf was initially proposed as a refrigerant in mobile air conditioners. Daviran et al. [19] used R1234yf instead of R123a to simulate automotive AC systems. Experiments show that under the same working conditions, because R1234yf has a smaller pressure drop, its performance is better than R134a. At the same time, it can effectively increase the COP, improve the durability of the compressor, and make the pipeline system more portable and economical. Similarly, Cho et al. [20] proposed the R1234yf system with internal heat exchanger and conducted experiments. Experiments have found that the cooling capacity of the system when R1234yf is used as the refrigerant is the same as when R134a is used. The problem of refrigerant substitution needs to be solved. The advantages and disadvantages of refrigerants are summarized in Table 2.

**3.2. Refrigerant injection systems**

In order to solve the problem of low efficiency of EV traditional ASHP systems, especially in low-temperature outdoor environments, EV refrigerant injection systems have been proposed. Injecting vapor refrigerant during the compression process can increase the mass flow rate of the refrigerant flowing through the compressor, thereby

**Table 2.** Comparison of different refrigerant systems with R134a [21,22].

Type	GWP <sub>100</sub>	Features
R134a	1300	High GWP, non-flammable, pressure ratio needs to be adjusted at low temperature, high energy consumption in winter, high emissions.
R152a	138	Low GWP, flammable, high COP, low temperature requires pressure ratio adjustment, heating capacity similar to R134a, high energy consumption in winter, and relatively good reduction in total emissions.
R1234yf	<1	Low GWP, low flammability, pressure ratio needs to be adjusted at low temperature, heating capacity is similar to R134a, high energy consumption in winter, and relatively good reduction in total emissions.
R290	5	Low GWP, highly flammable, high COP, heating capacity between R134a and R410A, the best reduction in total emissions.
R410a	1130	High GWP, non-flammable, heating capacity about 3 times that of R134a, high emissions.
R32	677	GWP is between R134a and R1234yf, low flammability, heating capacity is about 3 times that of R134a.
R744	1	Low GWP, non-flammable, highest heating capacity, high emissions.

effectively improving the efficiency of the system and improving its working performance.

Using a steam injection system is one of the ways to improve the system's capacity. Kwon et al. [23] proposed an internal heat exchanger type vapor injection HP system (Figure 3) for EVs, it adds a heat exchanger, electronic expansion valve and an injection compressor. The system increases the compressor power and the heat recovery, and improves the performance of the HP.

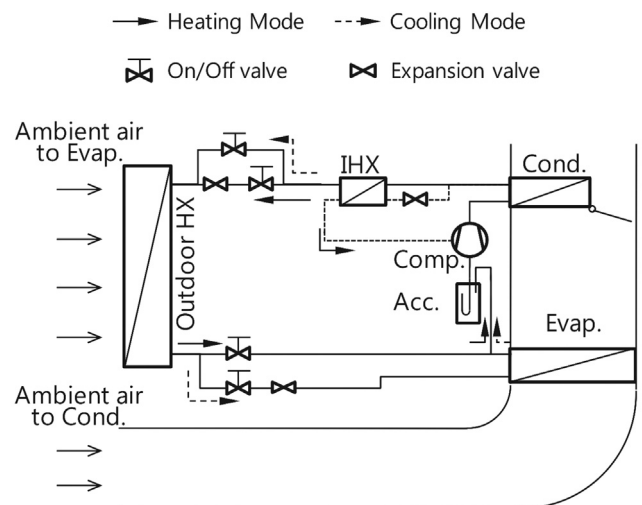
Qin et al. [24] designed and tested an ASHP system for refrigerant injection in EV. As the results show, the heating capacity of the system can be increased by 31% when refrigerant is injected.

The injection pressure and the angle of the injection-port will affect the performance of the vapor injection HP system. Qin et al. [25] researched and developed a test bench for EV in cold areas that can be converted between traditional and refrigerant injection ASHP systems, designed and manufactured two scroll compressors with injection holes, and the impact of the form of the injection holes on the performance of the system and refrigerant circulation was analyzed. The experimental results show that the heating capacity of the refrigerant injection ASHP system is 28.6% higher than that of the traditional system. Jung et al. [26] studied the impact of injection port angle and IHX length on the steam injection HP system of EVs under different starting conditions. Experimental data show that the system performance is best when the length of the IHX is 300 mm and the injection port angle is 400°.

Different injection positions and pressures will also affect system performance. Choi et al. [26] tested the conditions of the system when injecting steam at multiple injection positions and intermediate pressures, and determined the best injection position of the steam injection system under low temperature conditions. Wang et al. [27] proposed a method that can predict the performance of the steam jet HP system. In addition, Qin et al. [28] discussed the influence of compressor speed and refrigerant injection state of the system, confirmed that the refrigerant injection can indeed improve the heating performance of the system, but the complexity of the system has also been improved to a certain extent.

**3.3. Secondary loop systems**

Traditional EV air source HP will be negatively affected when the system runs under low ambient temperature, which will consume more battery power and affect the driving range in cold areas [29]. Aiming at the problem of low heating performance of EV in low temperature environments, the secondary loop systems have been proposed. Li et al. [30] established and studied a secondary loop HP system (Figure 4), and



**Figure 3.** Schematics of internal heat exchanger type vapor injection HP system [23].



measured the system COP and compressor power consumption parameters under different working conditions. Li et al. [31] also conducted similar experiments and found that the system performance of the secondary loop is better, especially at low temperatures, the system performance is significantly better than the traditional direct system.

In addition, the secondary loop can also solve the degradation of system performance caused by frost in a low temperature environment [32]. Li et al. [33] proposed a secondary loop system and studied its antifreeze performance under various low temperature conditions. They found that the heating efficiency and anti-frost ability of the secondary loop system have been improved.

### 3.4. HP systems with dehumidification and defogging function

Although the traditional HP system has a simple structure and low cost, it cannot remove the fog on the inner surface of the windshield when driving in cold weather, which will affect the visibility and safety of driving. Instead, an improved HP system with defogging function is used. Chang et al. [34] proposed a high-voltage AC system with defogging function suitable for EVs, the structure of which is shown in Figure 5. In the defogging mode, when the refrigerant evaporates in the HX2, it cools and dehumidifies the indoor air, the indoor air passes through the HX1 to generate dry hot air, and then directly enters the windshield for defogging.

Zhang et al. [35] considered from another point of view, and proposed a method of rationally utilizing the return air and fresh air, using a continuous anti-fog air curtain on the front windshield. This method can not only prevent the generation of fog on the inner surface of the windshield, but also has a certain energy saving potential. When the return air ratio is 0.46, the maximum energy saving rate can reach 40.6% compared with the fresh air condition. Na et al. [36] introduced a desiccant coated heat exchanger is introduced into the system for dehumidification. In the process of heat exchange, the moisture in the air is adsorbed into the desiccant of the heat exchanger to achieve the purpose of demisting. However, the adsorption performance of the heat exchanger will decrease with the increase of water vapor adsorption, so it is necessary to have the regeneration process of the adsorbent in a certain period of time.

### 3.5. HP systems with novel heat exchanger

Because during the heating process, the temperature of the outer surface of the outdoor heat exchanger of the HP system is low, which will cause the liquid in the air to condense [37, 38]. Once the temperature of the outer surface of the heat exchanger is below the freezing point, frost will form on the surface of the heat exchanger. Therefore, new heat exchangers have been proposed to improve the performance during frosting and defrost.

Compared with traditional heat exchangers, louvered micro-channel heat exchangers can delay frost formation [39]. Hong et al. [40] developed a new type of micro-channel heat exchanger, which increased the frosting period and peak heating capacity by 102.7% and 14.0% compared with corrugated louver fin heat exchangers.

Mahvi et al. [41] developed a superhydrophobic heat exchanger, as shown in Figure 6, and tested its performance. The results showed that the COP of the device was higher than the traditional system in the first 2 h after opening, and it was twice as high as the super-hydrophilicity system.

## 4. Adsorption air conditioning systems

Even though the vapor compression heat pump AC system seems to be able to meet the heating requirements in most cases, its heating performance will be affected by the environment and significantly decrease when the ambient temperature is extremely low. In addition, same as PTC heating, the use of vapor compression heat pump air-conditioning systems will also produce additional power loss, but AAC can avoid this problem [42]. In the AAC system, the compressor is replaced by a adsorption reactor, and the system structure is shown in Figure 7. During the charging process of the EV, the adsorption reactor absorbs heat, and the refrigerant flows from the adsorption reactor into the liquid storage tank. During the heating process, the refrigerant flows from the liquid storage tank into the evaporator, the adsorption reactor heats the cold air in the cabin, and at the same time absorbs the steam in the evaporator to complete the heating process. This system usually uses NH<sub>3</sub> as the refrigerant because it is well matched to the adsorbent to form a working pair and will not freeze at low temperatures.

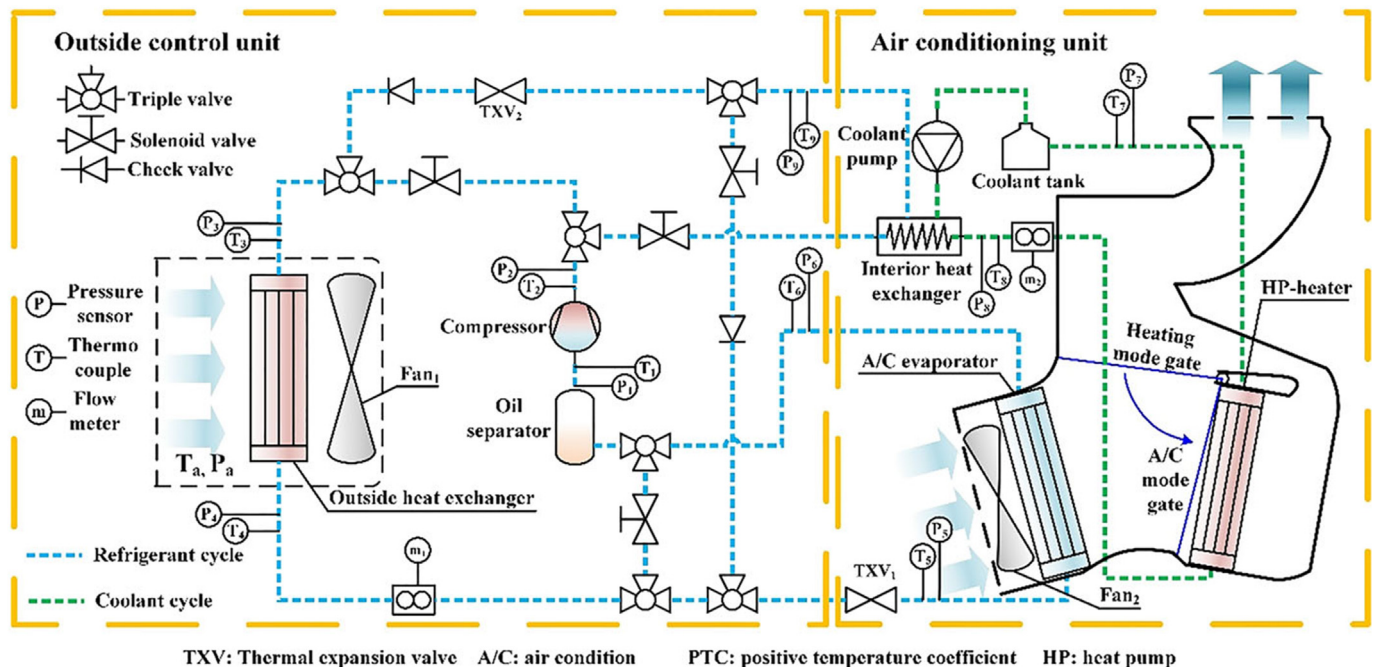


Figure 4. A schematic of secondary loop ACHP system [30].

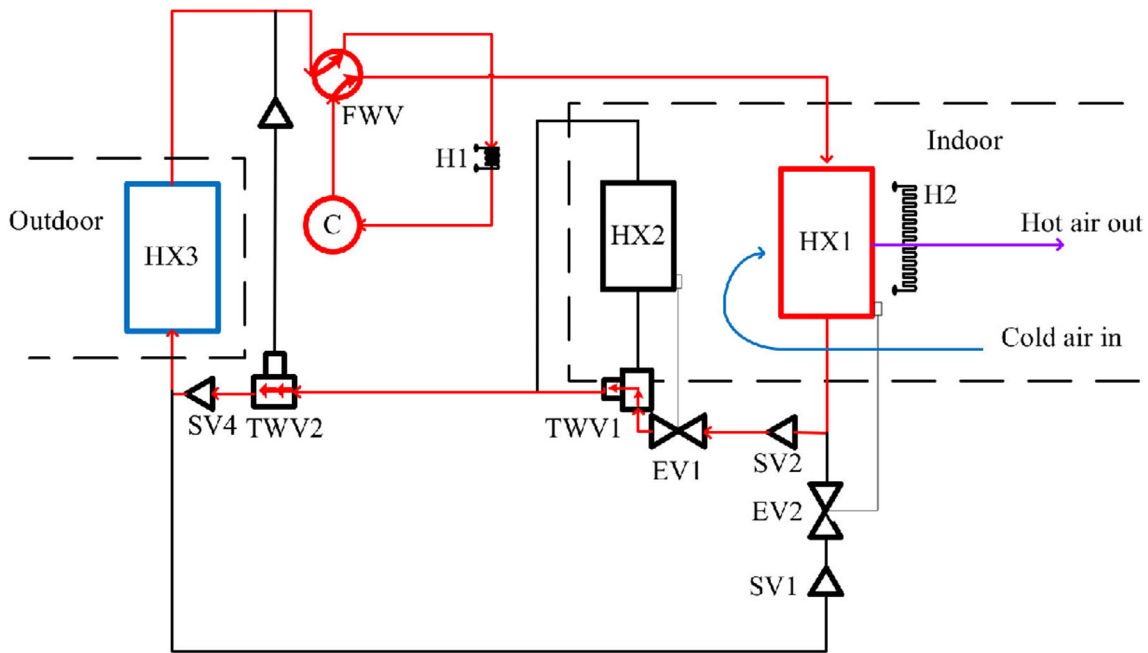
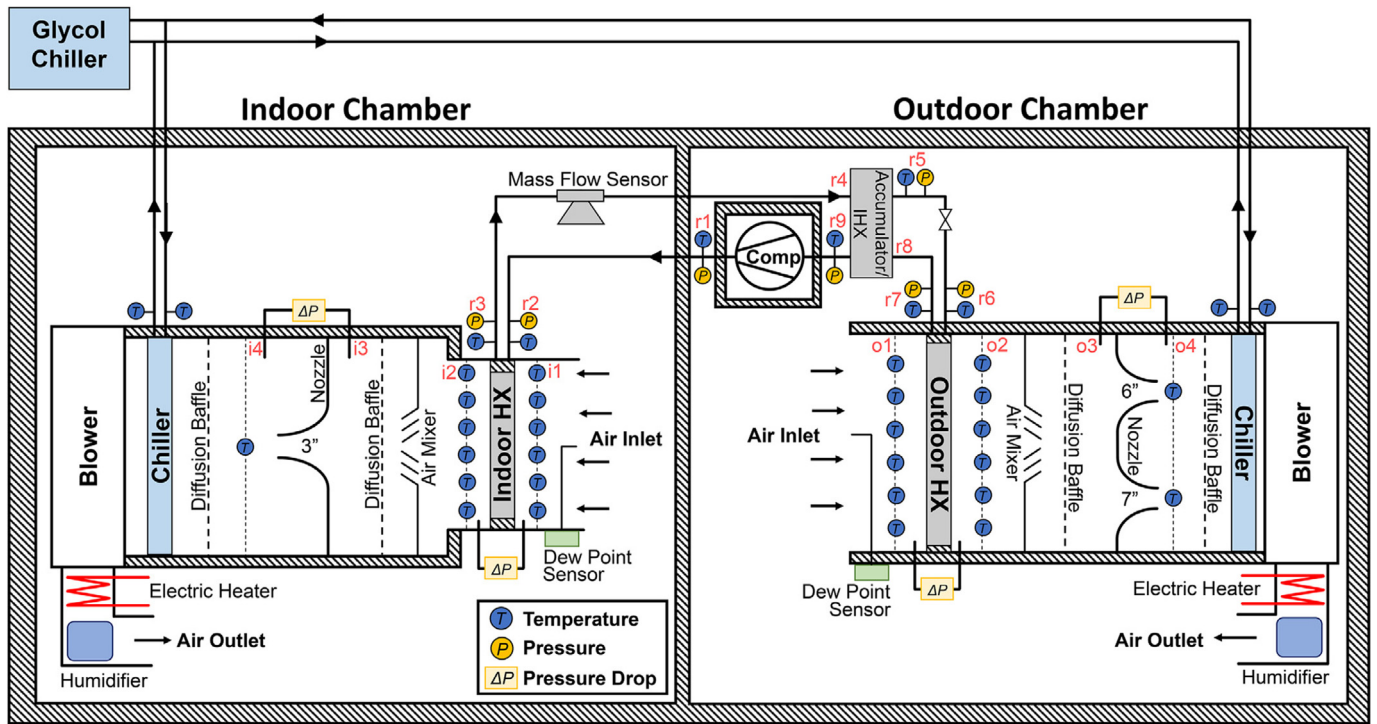


Figure 5. Schematic diagram of experimental high-voltage AC setup [34].



\*Drawing not to scale

Figure 6. Schematic of a superhydrophobic heat exchanger [41].

Jiang et al. [44] proposed a new type of AAC using expanded natural graphite as a sorbent for heating the cabin of an EV, and evaluated its impact in terms of energy density, energy efficiency, extra mass, and mileage savings. The results show that the additional mass has a limited effect on the EV's driving range. During the experiment, the EVs of the selected models can save nearly 100 km of driving range when heated by AAC, which can significantly reduce the energy consumption of EVs. At the same time, the energy density and efficiency of the system are positively correlated with the changing trend of refrigerant vaporization

temperature, and the range of COP is from 0.34 to 0.82 under different vaporization temperatures and mass ratios. Wajid et al. [45] provided a solar AAC and confirmed its feasibility.

An et al. [43] studied the influence of ambient temperature on EVs using AAC, and determined the best solid adsorption working fluid in different temperature regions. Because the adsorption process progresses smoothly and the adsorption effect is better when the temperature difference between the adsorption reactor and the evaporator is small, the results show that  $MnCl_2$  is recommended as the adsorption in severe cold areas,  $CaCl_2$  is

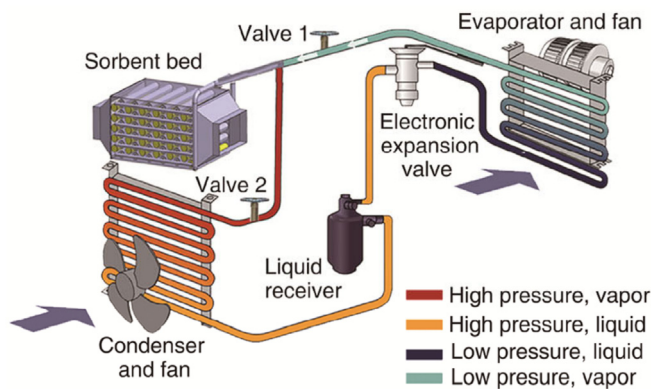


Figure 7. Adsorption type ACs for EVs [43].

recommended as the adsorption in warm areas, and other places can use a mixture of  $MnCl_2$  and  $CaCl_2$ . Shabir et al. [46] also tested different sorbents and determined the most suitable sorbent for different systems.

### 5. Fuel combustion systems

If a system separate from the battery system can be used for heating alone, it can also achieve the purpose of reducing battery loss and reducing vehicle mileage. A thermally efficient heating system with fuel burners is proposed to achieve this possibility by directly heating the air in the passenger cabin by exothermic combustion of the fuel. At the same time, it should be noted that an independent heating system means a larger footprint and heavier weight, which means that the combustion system is more used in extremely cold areas to reduce mileage, and is not suitable in colder areas [47].

Cho et al. [48] proposed the use of FC system as an auxiliary heating method for EVs to heat the air in the cabin and at the same time control the flow of high-temperature exhaust gas to the heat exchanger. The results show that based on this system, the mileage of the EV can be reduced to 40% of the mileage when the original heating system is used when heating at an ambient temperature of 0 °C. Seo et al. [49] proposed a system with a fuel burner that can be used to heat the car battery in an electric car cabin at the same time. The structure is shown in Figure 8, and its heating characteristics have been measured, which further confirms its feasibility.

Burners that use biological materials as fuel are also full of prospects, and bioethanol is a good choice. Carbon dioxide emissions when burning ethanol for heating are much lower than those when burning gasoline, while the energy density of ethanol is higher than that of gasoline, which

makes it popular. Kohle et al. [50] proposed a FC heating system based on ethanol combustion. Compared with electric heating, its mileage has been significantly reduced, which shows that it is very effective to combine environmentally friendly fuels with FC burners. Riess et al. [51] also proposed a heating system that uses ethanol as fuel, and reached a similar conclusion that the independent combustion heating system can significantly optimize the battery when the EV is driving in a very cold environment. I believe that more efficient and energy-saving fuels and burners will be appeared in the future.

### 6. Heat storage heating systems

As the current heating system, especially PTC heating, will reduce the mileage of EVs. In addition, EV heating is intermittent, in order to reduce energy consumption, HS systems have become more and more important [52]. Replacing the original heating system of the EV with a heat storage device can reduce the burden of heating on the car battery, break the air conditioner's dependence on electricity, make car batteries last longer and protect the environment [53].

Phase change energy storage is a good choice for reducing energy consumption, which usually chooses beeswax or paraffin as the phase change material (PCM), and its requirements for motor output are extremely low. The performance of different PCM was evaluated by Putra et al. [54]. The results show that the thermal conductivity of beeswax is low, but it has large sensible and latent heat, which can store a large amount of thermal energy. At the same time, when the melting temperature of RT44HC is within the recommended range of battery operating temperature, RT44HC is also a good choice.

Xia et al. [55] proposed a phase change energy storage design using paraffin as the phase change material combined with heat pipe heat exchange. The system stores heat in the heat storage device when the EV is not working, releases the stored heat during operation, and uses the phase change of the working liquid in the heat pipe to deliver heat to the vehicle. The system mainly includes four parts: heating device, heat storage device, heat transfer device and control device. The PTC heater is selected as the heating device, and the device uses the cross arrangement of the PTC heating plate and the heat pipe to improve efficiency. The heat storage box is wrapped with nano-aerogel composite thermal insulation material to reduce heat dissipation loss. Tests show that the device can continue to provide heat for 2 h.

### 7. Waste heat recovery heating systems

During the operation of EVs, a large amount of energy is lost in the form of heat energy through various channels such as batteries and

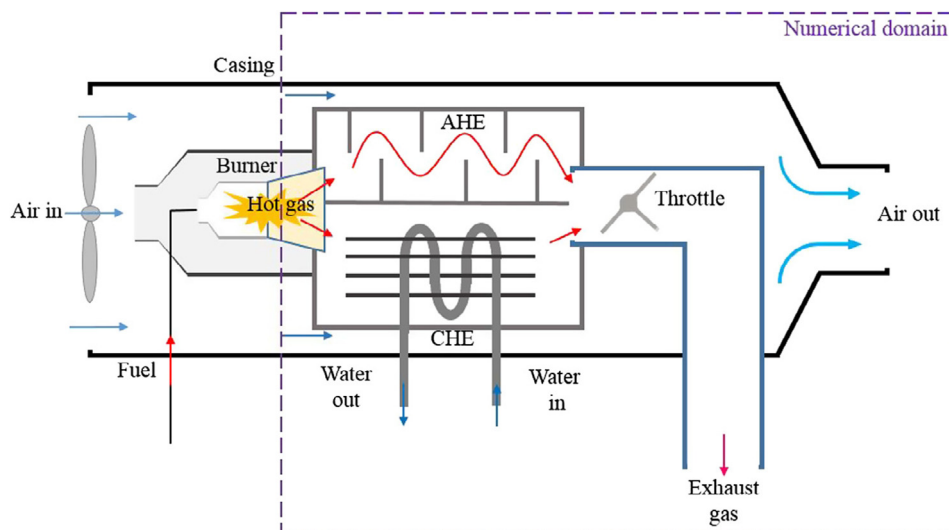


Figure 8. Schematic diagram of the integrated heating system [49].



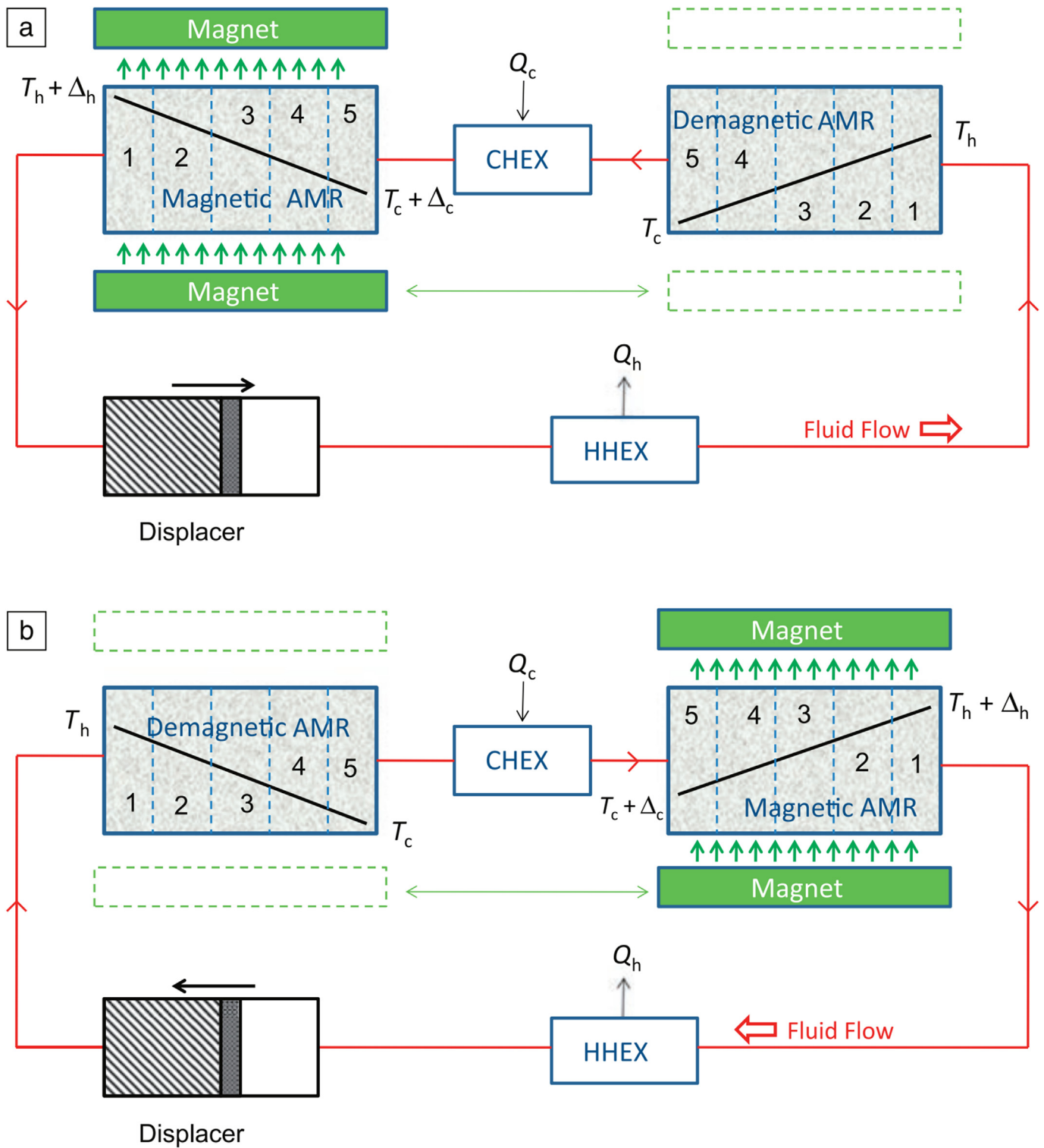


Figure 9. Schematic of the active magnetic regenerator cycle [62].

electrical equipment. If the waste heat can be recovered and the heat extracted from it and reused in the vehicle propulsion system, fuel consumption can be reduced, thereby improving battery performance [56]. In the waste heat recovery heating system, the air with waste heat exchanges heat with the refrigerant in the heat exchanger, and the refrigerant evaporated by the waste heat enters the compressor and is compressed to release heat to the air in the EV to convert the waste heat into heat capacity.

Under normal circumstances, WHR will have a positive impact on the COP of the system. Tian et al. [57] proposed an EV thermal management system with motor and controller unit WHR, and analyzed its performance. The results show that under the best working conditions, using the WHR system, the COP of the vehicle is between 2.05 and 4.71 under different condensation temperatures, which is a maximum increase of 13.2% and a mileage increase of 33.64% compared with the traditional system without it.



However, when the temperature is higher, the situation changes. Han et al. [58] proposed an air source HP system with WHR for electric buses to improve heating performance. Experiments have found that when the outside temperature is below  $-5\text{ }^{\circ}\text{C}$ , recovering waste heat can improve system performance. However, when the temperature rises, the pressure drop of the waste heat exchanger becomes larger, and the recovery of the waste heat will adversely affect the performance of the system.

In order to solve the negative impact of temperature on the WHR system, Ahn et al. [59] proposed to investigate the feasibility of dual-source heat pumps using air and waste heat in EVs, and compared the system performance of the three cases of air source only, waste heat only and dual heat source. The study found that the heating performance of the dual heat source mode is higher than that of the pure air source and pure waste heat mode, and at the same time, good results can be obtained by operating in the mode at higher temperatures.

Due to the limited capacity of EV batteries, in order to balance the supply and demand relationship between EV power demand and waste heat recovery, Merhy et al. [60] proposed an energy strategy based on a multi-objective and multi-criteria optimization algorithm, which can be based on power supply and demand conditions. Control the energy flow of the EV and decide whether to recover the waste heat. The reliability of this strategy is verified by simulation, and it provides a reliable solution for the optimization of vehicle energy flow of waste heat recovery system.

## 8. Magnetocaloric effect

Active magnetic regeneration (AMR) as a reversible thermal cycle technology that can be used for heating, cooling and mechanical power generation, and can even reach 60% Carnot efficiency it is one of the most promising alternative technologies for the development of heat pumps [61]. The magnetic HP system is based on the AMR principle. It uses the magnetocaloric effect (ME), which is a characteristic of certain magnetocaloric materials. When the applied magnetic field changes, it heats or cools, so that it can use the heat dissipated by the magnetocaloric material when it is applied by an external magnetic field to heat the refrigerant and then supply heat through the heat sink. Since the heat transfer process of magnetic heat pumps does not require liquid phase change, fluid heat transfer liquids can be used without the need for fluorinated refrigerants or other gaseous refrigerants, which reduces the possibility of impacting environmental benefits. In addition, since the working medium of the magnetocaloric system is a solid with a high entropy density instead of a gas, the system can be easily miniaturized to reduce the burden on operation due to the volume and weight of the system.

Zimm et al. [62] proposed an AMR-based active magnetic regenerator cycle, and the system principle is shown in Figure 9, and made some progress. Plait et al. [63] Proposed a heat pump technology based on ME and applied it to the cabin heating system of automobile to replace the traditional heating system. They modeled the ME system and evaluated its implementation in EV. The results show that the ME system can meet the heating demand of cabin space, and the heating power can be higher than that when using batteries, which shows that it is possible to use ME system for heating in the future. Lyskawinski et al. [64] also revealed that the magnetic heating method was compared with the traditional method, which confirmed its feasibility. However, it should be noted that the energy efficiency of the magnetocaloric cycle is low, the temperature span caused by each cycle is limited, and its current heating capacity depends heavily on the cycle efficiency. Therefore, the search for magnetocaloric materials with better performance is still the future topics to discuss.

## 9. Thermoelectric effect

TE can realize the conversion between heat and electricity. A thermoelectric module based on this principle converts voltage into temperature difference. The thermoelectric heating module is composed of a group of semiconductor thermocouples of different materials. When a certain voltage is applied to the junction of the thermocouple connection, one side of the thermocouple pair will absorb heat, while the other side will release heat. The heat is transferred to the air inside the EV through the radiator. Compared with the traditional vapor compression cycle, thermoelectric modules are less efficient, but they are small in size, light in weight, fast in heating, require no refrigerant, and have a high COP [65]. Cosnier et al. [66] proposed the heating system model using thermoelectric module, the COP can reach about 2 during heating, and the temperature difference between the cold side and the hot side can even reach  $70\text{ }^{\circ}\text{C}$ , confirmed the feasibility of heating air with thermoelectric modules.

The heating system using the thermoelectric module is relatively safe and stable when working, directly converts electrical energy into heat energy, and its power changes with the current value and voltage value acting on the system, which can accurately control the temperature, so it is very suitable for the adjustment of local thermal environment.

Wan et al. [67] proposed and tested a local air-conditioning system for trucks using TE, with six thermoelectric modules placed at different locations around the driver. The results show that the system can obtain better cop and reduce operating energy consumption under the current of 3–6 A, and it can meet the driver's thermal comfort requirements.

**Table 3.** Summary of advantages and disadvantages of different technologies for heating EVs.

System type	Advantages	Disadvantages
PTC heating systems	Directly heats the air with fast heating speed; high system efficiency.	High energy consumption, seriously affecting vehicle mileage; complex structure, many parts and components; high cost.
Vapor compression heat pump systems	High system efficiency and good economy; good adaptability; slightly higher mileage than PTC.	Poor performance at low temperature, limited by temperature range; high cost.
Adsorption air conditioning systems	Lower battery capacity requirements, significantly reducing battery weight and operating costs; longer mileage.	Finding the best adsorbent-adsorbate pair is challenging; initial investment is higher; efficiency is lower than heat pumps.
Fuel combustion systems	No dependence on the main battery of EVs; increased cruising range; high efficiency.	Heaters require space and additional refueling burden; high cost.
Heat storage heating systems	Low demand for batteries; greatly prolongs the mileage of the EV and the service life of the battery; energy saving and environmental protection; takes up less space in EVs.	The continuous heat supply time is short; low efficiency.
Waste heat recovery heating systems	Low energy consumption; improved battery performance; great savings in tram mileage; moderate efficiency and high efficiency.	Energy efficiency is heavily dependent on waste heat; at lower temperatures there is insufficient heat supply and can only be used as auxiliary heating.
Magnetocaloric heating systems	Small size, light weight, no pollution; few moving parts, low vibration and noise; high reliability, long life, and easy maintenance.	The temperature difference produced by each cycle is small; the heat exchange rate is slow.
Thermoelectric heating systems	No refrigerant and moving parts; compact structure; precise temperature control, suitable for local thermal environment regulation.	Low efficiency, low heat production; the issue of developing higher performance TE materials remains to be resolved.

## 10. Conclusion

In this article, a comprehensive review of the latest technology of EV heating systems, analysis of existing systems, technologies and challenges in this field, the conclusion is as follows: The PTC system was once the most popular heating system, with the advantages of low thermal resistance and high efficiency. However, due to its poor fuel economy, it is gradually replaced by HP system. The HP system has strong heating capacity and higher economy. The replacement of refrigerants used in HP systems and new circulation methods are being actively discussed. However, the HP system still has the problems of poor low-temperature performance and surface frosting, which need to be solved urgently. But these problems can be solved by coming up with better performance mixed or natural refrigerants, better systems such as refrigerant injection systems and secondary loop systems, innovative dehumidification and defogging methods, special materials for heat exchangers, and this is also the future research needs to be considered.

In addition, other novel technologies are investigated and proposed to reduce the energy consumption of EV's heating system. The adsorption heating system can reduce battery consumption and save the mileage of EVs. Fuel combustion heating with a separate heating system can significantly increase vehicle mileage with high heating efficiency. The development of heat storage and waste heat recovery systems can make use of heat from environment or the EV themselves in order to reduce the burden on batteries and extend the life of car batteries. The application of magnetocaloric effect and thermoelectric effect also makes the EV heating system more environmentally friendly.

Table 3 shows a brief comparison between the previous major EV heating technologies, including advantages and disadvantages. It helps design engineers understand and select specific available technologies for practical applications.

From the perspective of energy saving and environmental protection, the above technologies are likely to be used as a supplement or alternative to the vapor compression heat pump technology in the future. However, the problems that still need to be solved are to find a better matching adsorption working pair, a system with more reasonable structure, a phase change material and a magnetocaloric material with a better performance, a better combination of the waste heat recovery system and the optimization of the whole vehicle energy flow, and the more reasonably distribution of thermoelectric modules should be arranged in the case of local heating. The pursuit of more efficient and energy-saving EV heating systems is a permanent theme of exploration, and only the joint efforts of all researchers can promote its continuous development.

## Declarations

### Author contribution statement

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No data was used for the research described in the article.

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The authors declare no conflict of interest.

## Additional information

No additional information is available for this paper.

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