Annex III - Technical Institute of Physics & Chemistry, Chinese Academy of Sciences (CAS), 2023 - relevant robust extracts/summaries in English.

Research Report on Development of Electric Vehicle Heating Technology (Excerpt)

Chinese Academy of Sciences Lihua Institute of Technology

2.4.4 Environmentally friendly working fluid heat pump

R1234yf heat pump system

R1234yf is an environmentally friendly refrigerant for automotive air conditioning. Because its performance approximates to that of R134a, it is regarded as one of the more promising new-generation alternative refrigerants for automotive heat pump systems.

R1234yf offers potential advantages over R134a. When the heat pump works at a relatively low ambient temperature (a temperature below -20° C), the suction evaporation pressure may be lower than the atmospheric pressure and a vacuum negative pressure could occur, causing air and moisture to leak into non-sealed components, and leading to system damage. The compressor would therefore be unable to run at the highest speed; its speed would have to be reduced to ensure that the suction pressure was greater than the external atmospheric pressure. However, reducing the compressor speed also leads to a sharp drop in heating performance at low temperatures. Figure 0-1 shows a comparison of the low-pressure saturation curves of R1234yf and R134a. From Figure 0-1, it can be seen that the low-pressure saturation pressure of R1234yf is about 15 per cent higher than that of R134a. Comparison with atmospheric pressure shows that the saturation pressure of R134a is as low as atmospheric pressure when the saturation temperature is about -25° C, and that R1234yf at saturation temperature reaches atmospheric pressure only at -29° C. Therefore, R1234yf is able to apply lower evaporation pressure; namely, in the same low-temperature environment, R1234yf can match a higher compressor speed than R134a and provide higher heating capacity.

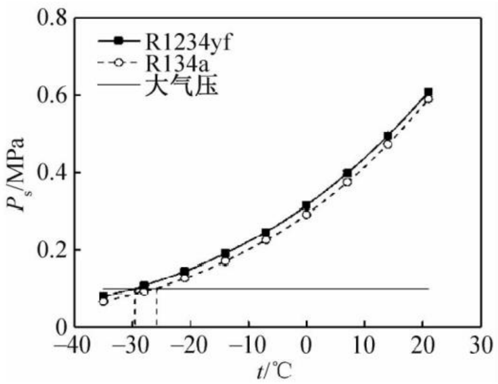


Figure 0-1 R1234yf and R134a: Comparison of low-pressure saturation curves[52]

The discharge temperature of the compressor is one of the important parameters that affects the stability of the system. If that temperature is too high, the volumetric efficiency of the compressor will decrease and power consumption will increase. Overheating of the discharge, moreover, will also cause adverse reactions and wear and tear between the lubricating oil, refrigerant and other components. This will seriously affect system stability and safety, and reduce the service life of the compressor. Y. [49]Lee et al. conducted experiments on the R1234yf and R134a systems and their results indicated clearly that R1234yf's discharge pressure is lower than that of R134a by 6.4–6.7°C. R1234yf, therefore, is able to provide a lower discharge temperature for the system and make the compressor run with greater stability.

There are currently numerous Chinese and overseas scholars who have conducted research on R1234yf used in vehicle air conditioning systems. There are many scholars who, in the course of their research, have conducted direct substitution experimentation and analysed performance in cold conditions. Li et al.[233] studied the heating performance of the electric vehicle R1234yf heat pump system in cold climates. The principal aspects studied were the effects of charge amount, compressor speed, outdoor wind speed, outdoor temperature, indoor flow rate, indoor temperature, condenser width, and presence or absence of steam injection on the heating performance of the system. The results show that increasing the width of the internal condenser by 10 per cent or using steam injection technology can give R1234yf a higher heating capacity and COP than R134a. Wang et al.[53] replaced the existing R134a automotive air conditioning system with the refrigerant R1234yf without any modification. Depending on the operating conditions, the performance of the system will drop by 0–27 per cent. By introducing internal heat exchangers, injectors or expanders, or adjusting thermal expansion valves, the performance of the R1234yf system can be improved to the same level as the original R134asystem. The study also found that the heat transfer performance of R1234yf in the evaporator is equivalent to that of R134a. However, the heat transfer performance in the condenser is not as good as that of R134a. Therefore, the condenser of the R1234yf system needs to be further optimized. At the same time, because of the larger friction drop of R1234yf, the volumetric efficiency of R1234yf is slightly lower than that of R134a. The lubricating oil used in the R134a system can be used in the R1234yf system, and there is no significant difference in the oil circulation ratio of the two refrigerants. Lee et al.[49] tested the performance of R1234yf and R134a on a heat pump test bench. The results made clear that, under the same conditions, the COP and heating capacity of the R1234yf system were respectively 2.7 per cent and 4 per cent lower than those of the R134a system. Moreover, the compressor discharge temperature of the R1234yf system is lower in winter conditions, while the charge of R1234yf is about 11 per cent lower than that of R134a because of the lower density of R1234yf.

Since the latent heat of phase change of R1234yf is lower than that of R134a under the same common working temperature range (-25 to 40° C) and the same working pressure, this causes the enthalpy difference in the medium condensation and exothermic process of R1234yf to decrease when directly replacing R134a. Although R1234yf has a high gas phase density and increases the refrigerant flow rate, it still cannot fully make up the enthalpy shortfall, so the heating performance of the system is slightly lower. The working capacity of R1234yf is therefore slightly different from that of R134a.

In order to narrow the energy efficiency gap between the R1234yf heat pump system and the R134a heat pump system, many scholars in China and abroad have in recent years conducted research on the R1234yf heat pump system.

Sad[234] compared the theoretical performance of the R1234yf and R134a theoretical cycles under the same operating conditions. The analysis results show that the R1234yf system has a lower cycle pressure ratio and exhaust temperature than the R134a system, but also that the theoretical COP is lower than that of the R134a system. On this basis, comparative experiments were conducted. The results showed that the cooling capacity of R1234yf decreased by up to 13 per cent, COP decreased by up to 11.8 per cent, and the compressor discharge temperature decreased by up to 15° C. Zhao[235] et al. also conducted a comparative study on the performance of R1234yf and R134a, and found that the optimal refrigerant charge of the R1234yf system was 95 per cent of that of the original system. The cooling capacity and COP of the R134a system are respectively up to 12.4 per cent and 9 per cent higher than that of R1234yf. In addition to the performance testing of the R1234yf direct replacement system, Zilio[236] et al. also conducted a simulation study to improve the performance of the R1234yf system by changing the structure of the evaporator and condenser. The simulation results show that when the windward areas of the evaporator and condenser are increased by 20 per cent and 10 per cent respectively, the R1234yf system can achieve higher COP. Qi[237] et al. compared the performance of the R1234yf system and the R134a system using different evaporator forms (tiered and microchannel). The experimental results found that the R134a system can obtain better heat transfer and flow performance when the tiered heat exchanger is used, while the R1234yf system is more suitable for microchannel heat exchangers.

Li Yanhui et al.[238] built a set of electric vehicle heat pump air conditioning systems, whose principles are as shown in Figure 0-2. Under the conventional system, the refrigeration performance of R1234yf is 5.6–7.5 per cent lower than that of R134a, while COP is 5.4–7.1 per cent lower. By adding heat regenerators and regenerative air coolers and increasing compressor speed, the gap between R1234yf's cooling capacity and COP and those of R134a will be less than 1 per cent.

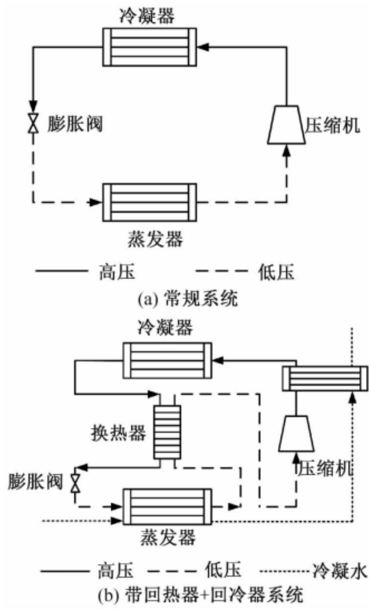


Figure 0-2 Electric vehicle air conditioning system cycle theory[238]

Zou Huiming et al.[239] built a heat pump air conditioning system for electric vehicles, and compared the performance of the R1234yf and R134a heat pump systems under different working conditions. Figure 0-3shows the comparison of the system heating capacity and COP of the two refrigerants at different indoor and outdoor temperatures and compressor speeds of 3000, 5000, and 7000 rpm, respectively. When the indoor and outdoor temperature difference was greater than 20°C, in order to protect the compressor, the test was not carried out under the condition of a rotating speed of 7000 rpm. Figure 0-3 shows that the difference between the heating capacity and COP of the two systems is within 10 per cent. This difference has a lot to do with the opening of the expansion valve, the speed of the compressor, and the air volume.

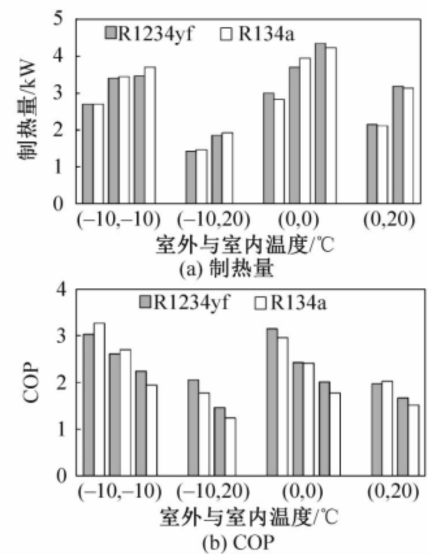


Figure 0-3 R1234yfandR1234aheating performance comparison[239]

The use of enhanced vapor injection (EVI) technology can improve the cycle stability and performance of the R1234yf system by increasing the enthalpy difference in the evaporator. Zhang Ziqi et al.[240] tested the vapor injection of the R134a heat pump system in a low-temperature environment. The system's heating capacity increased with the increase in air supply pressure, and the lower the ambient temperature, the better the effect of vapor injection. When the ambient temperature is -20°C, the average heating capacity in EVI mode increases by 57.7 per cent. When the ambient temperature is -10° C, the average heating capacity in EVI mode increases by 44.1 per cent. A more appropriate optimization of the economizer can increase COP and heating capacity by about 14 per cent. Therefore, vapor injection is able to solve the problem of the decline in heating performance of the heat pump system at low temperatures very effectively. The physical properties of R1234yf are very similar to those of R134a, and because of the higher gas phase density, can provide higher mass flow rate. Therefore, R1234yf will be more suitable for the vapor injection system than R134a, and the improvement in heating performance is also better than that of R134a. Liu Yusheng et al.[241] have studied the R1234yf system suitable for ultra-low temperatures at -20°C. As shown by Figure 0-4, by adopting vapor injection technology, the heating capacity and COP of the R1234yf system in a low-temperature environment of -20°C can reach 2kW and 2.0 or above, the heating capacity and COP of the improved new heat pump have increased by 30 per cent and 14 per cent respectively, and its heating capacity is basically the same as that of R134a, while the effect of vapor injection is better than that of R134a refrigerant.

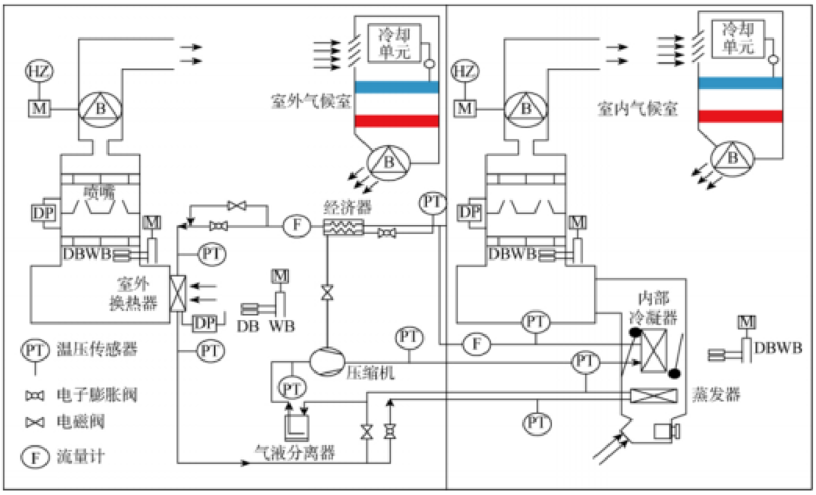


Figure 0-4 Ultra-low temperature vapor injection heat pump air conditioning system for vehicles based on R1234yf[241]

In addition, adding a heat regenerator to the system can also improve the performance of the R1234yf system. The heat regenerator exchanges heat between the high and high-pressure refrigerant liquid at the outlet of the condenser and the low-temperature and low-pressure refrigerant vapor at the outlet of the evaporator, so as to increase the sub-cooling degree of the refrigerant at the outlet of the condenser and improve the cooling performance of the system. Navarro [242]et al. added a heat regenerator with a spiral groove structure to the R1234yf system, which improved the cooling capacity and COP of the system, and basically reached the performance of the R134a system. This reduced the cooling capacity and COP performance loss of the R1234yf system by nearly 2 – 6 per cent. Cho[243] also introduced a heat generator into the system, causing something of a decrease in COP loss.

R744 heat pump system

The environmental performance of CO_2 (R744) refrigerant is excellent. It is also non-flammable and non-toxic, and low in kinetic viscosity and cost. Because of the excellent heating performance of CO2 at low ambient temperatures, CO_2 heat pumps have become a research hotspot in this field in recent years.

As a natural refrigerant, CO_2 refrigerant has thermodynamic properties compatible with refrigeration cycles and equipment. The latent heat of evaporation is relatively high, while the cooling capacity per unit volume is also quite high. CO2 refrigerant has good transportation and heat transfer properties. It has high thermal conductivity, low viscosity, and a large specific heat capacity. The liquid density and vapor density are relatively small, and the two-phase flow is relatively uniform at low pressure, which is conducive to the uniform distribution of refrigerant between the circuits after throttling. The small surface tension can improve the evaporation heat transfer coefficient in the boiling zone. The excellent flow and heat transfer characteristics can significantly reduce the size of the compressor and the system, making the whole system very compact.[54]

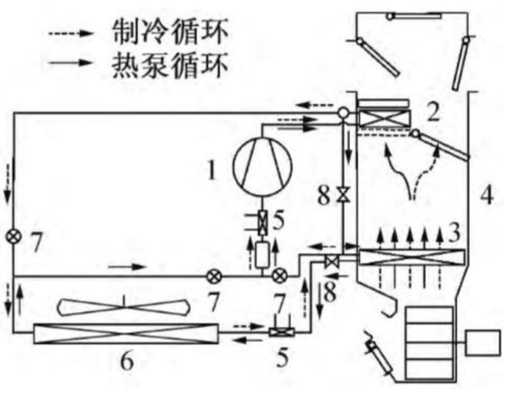
Since the critical temperature of CO_2 is very low, the exothermic process of the cycle is not condensation in the two-phase region, but occurs in the gas cooler in the region near or beyond the critical point. In recent years, many scholars and research institutions in China and abroad have conducted a great deal of research on the CO_2 heat pump systems of electric vehicles.

In China, Shanghai Jiaotong University has taken the lead in conducting research on CO_2 heat pump systems. Chen Jiangping[244] took the lead in developing the first CO_2 transcritical automotive air conditioning system test bench for vehicles in China. The measured cooling capacity reached 4.5kW under cooling conditions of 27°C/35°C. Jin Jifeng[245] designed the first parallel flow heat exchanger type CO_2vehicle air conditioning system in China by adopting microchannel heat exchangers with better heat transfer performance. The experimental results show that when the ambient temperature is 25°C, the cooling COP of the system reached 2.83. Actual vehicle road tests were then performed, and the results showed that because of the impact of the front-end module structure when the real vehicle was installed, the performance of the measured CO_2 automotive air conditioning system was far from that of the bench test, and its cooling speed was slower than that of the R134a system.

For the application of CO_2 vehicle air conditioning systems in electric vehicles, Wang [246,247]et al. tested the performance of the CO_2 heat pump air conditioning system of electric vehicles under typical operating conditions, and compared it with the R134a system. Through their experiments, it was found that the cooling capacity of the two systems is equivalent. However, when the ambient temperature increases from 27° C to 45° C, the cooling COP will drop from 2.0 to 1.3, which is 10 – 16 per cent lower than that of the R134a system. In heating mode, at -20°C/20°C, when the compressor frequency is 54Hz, the system's maximum COP reaches 1.7. Jiang[248] et al. tested the refrigeration performance of the system at different ambient temperatures. Their experimental results showed that when the ambient temperature increased from 35°C to 45°C, the cooling COP of the CO_2 air conditioning system weakened sharply, with a weakening rate as high as 37.7 per cent. Liu Yefeng et al.[249] designed a CO2 heat pump system for vehicles. Through simulation analysis, they obtained a COP 18.9 per cent lower than that of the R134a system, but the exhaust temperature was 45°C higher. The CO2 heat pump system has better performance. Wu Yue[250] et al. studied the effect of the CO2 heat pump system on the cruising range of a vehicle on a real vehicle. Through a comparison test with a PTC vehicle, it was found that driving in the normal mode at -5°C can increase the cruising range by 23.6 per cent, proving the economy of using a CO2 heat pump system in winter. Li et al.[251] proposed a CO_2 integrated fin micro-channel gas cooler for vehicle air conditioning. Their simulation results showed that the integrated fin and micro-channel gas cooler demonstrated good performance at high frontal wind speeds. The geometric shape of the fins and uneven distribution on the air side also had a certain impact on system performance.

The Korea Automotive Technology Research Institute has verified the feasibility and effectiveness of CO_2 air conditioning systems for automotive air conditioning through a series of studies on CO_2 air conditioning systems for cars. In 2009, Kim et al.[252] studied the performance of a CO_2 automotive air conditioning system under different operating conditions, and adjusted the system's operating conditions by changing the engine speed and vehicle speed. Their results showed that, with the vehicle idling but running under optimal exhaust pressure, the cooling capacity of the system exceeded 4.5kW, while the refrigeration COP exceeded 2.4. Under travelling conditions corresponding to 35°C/45°C, operating under the optimal exhaust pressure condition, the system's cooling capacity and cooling COP reached 7.5kW and 1.7 respectively. In 2012, Lee et al.[253] designed an electric drive CO_2 automotive air conditioning system, and experimentally tested the cooling performance of the system under variable working conditions. Their results showed that at 35°C, when the exhaust pressure increased from 9.2MPa to 10.2MPa, the cooling capacity of the system increased to 6.4kW, an increase of 36.8 per cent. The corresponding COP increased to 2.5, an increase of 30.3 per cent. When the compressor speed increased to 4500 rpm, the cooling capacity of the system generally exceeded 5.0kW. This exceeds the cooling load of automobiles in summer, and is sufficient to meet cooling needs.

In order to improve the performance of the CO_2 heat pump, Wang Dandong et al.[254] proposed to connect the indoor heat exchangers in series in the heating mode to improve the heat exchange capacity of the high-pressure side. As shown in Figure 0-5, the results show that, compared with a single air cooler, the heating capacity and COP_h of the vehicle heat pump air conditioning system using series of air coolers increased by 31 per cent and 33 per cent respectively.



1 压缩机; 2 室内气冷器; 3 室内蒸发器; 4 HVAC;
5 中间换热器; 6 室外气冷器; 7 电磁阀; 8 EEV。

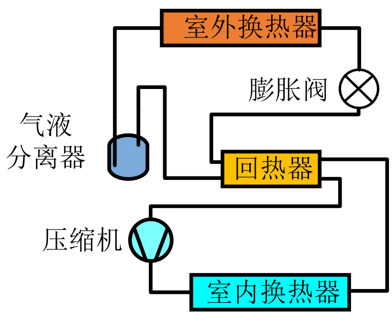
Figure 0-5 Adopting series air cooler CO_2 vehicle heat pump air conditioning system

Because of insufficient cooling capacity in summer and low heating efficiency in extremely cold conditions, many existing studies focus on improving the cooling performance of CO_2 heat pump systems in high temperature environments.

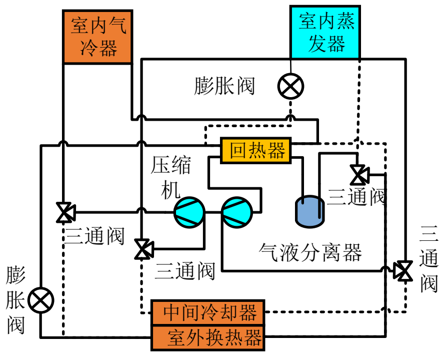
By adding a heat regenerator, the low-temperature refrigerant at the outlet of the evaporator can cool down the refrigerant at the outlet of the gas-liquid separator, thereby reducing the temperature before throttling, and improving system performance. Wang et al.[255] compared the thermal performance of the CO_2 heat pump system and the R134a heat pump system under the same test conditions. The results of their experiment showed that the CO_2 heat pump system and the R134a heat pump system had similar or even better cooling capacity and COP. In the heating mode, the performance of the CO_2 system was significantly better than that of the R134a system. The CO_2 heat pump system adds a heat exchanger between the expansion valve and the indoor heat exchanger, which can suit low-temperature environments. The results of the experiment show that the heating capacity of the system can reach 3.6kW when it is started in a low-temperature environment, and the COP is 3.15, which creates conditions[256] for the application of the CO_2 heat pump system in a low-temperature environment. The system is as shown in Figure 0-6(a). Cho et al.[257] confirmed that the use of the heat regenerator can not only improve the system's COP, but also increase its cooling capacity. At the same time, the system COPof the transcritical CO_2 cycle system with the heat regenerator can be increased by 11.9 per cent over that without the regenerator. Adding a heat regenerator, however, will make the exhaust temperature too high.

The research results show that the developed CO_2 heat pump system with an intercooler can significantly improve the performance[258] of the heat pump system. The intercooler is used to cool the refrigerant flowing out of the gas-liquid separator, reducing pre-throttle temperature, which can improve system performance. In the cooling mode, the compressor discharges the intercooling heat to the outside through the intercooler; in the heating mode, the intercooling heat is recycled through the indoor evaporator. The results of the experiment show that adding an intercooler can improve the thermal performance of the system. The system is as shown in Figure 0-6(b).

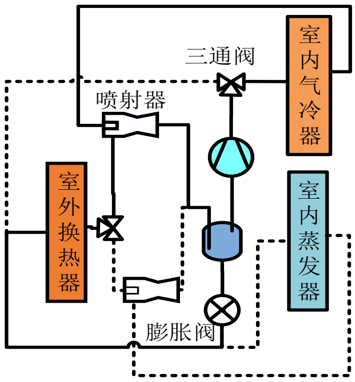
The CO_2 heat pump system replaces the throttle valve with an ejector. The refrigerant is ejected through the ejector, which can increase the inlet pressure of the compressor and reduce the working pressure ratio of the latter, so that the thermal performance of the CO_2 heat pump system can be improved.[259] The system is as shown in Figure 0-6(c). Li Hao et al.[260] developed a transcritical CO_2 vehicle air conditioning system with injectors and compared the improvement effect of the system performance under typical vehicle air conditioning conditions. Their results showed that, under different working conditions, the cooling COPof the injection system was 2.69 - 12.60 per cent higher than that of the conventional cycle, but the effect on increasing the the system's cooling capacity was not obvious. Zhang Zhenyu et al.[261] compared the refrigeration performance of the transcritical CO_2 vehicle air conditioning system with an ejector and the conventional cycle. The results showed that at an exhaust pressure of 11.3MPa, the cooling capacity and refrigeration COP of the system after the ejector was introduced were respectively increased by 6.6 and 6.1 per cent over the conventional cycle. The influence of the throat diameter of the ejector structure parameter on the system performance was analyzed, and it was found that a throat diameter of 1.08mm corresponds to the optimal refrigeration performance of the system.



(a) CO2 heat pump with heat regenerator



(b) Intermediate cooling CO2 heat pump



(c) CO2 heat pump with ejector

Figure 0-6 CO2 heat pump system schematic diagram[31]

R290 heat pump system

As an environmentally friendly refrigerant, R290 is currently widely used in the air conditioning industry. It has a low GWP and is environmentally friendly. The only disadvantage is that it is flammable and explosive. Existing studies have pointed out that R290 requires less compressor power and less refrigerant charging to obtain the same performance as R134a.[57] R290 is therefore expected to replace R134a to become an emerging environmentally friendly refrigerant.

Electric vehicles have been one of the emerging research fields in recent years and have received extensive attention from scholars. Many scholars have applied R290 to electric vehicles. Wu et al.[63] used R134a, R152a, R1234yf, R290, R410A, R32 and R744 for cabin heating and cooling of electric vehicles, and made a comprehensive evaluation. Among all refrigerants, R290 has the lowest CO_2 emissions. Liu et al.[64] pointed out that R290 can provide higher heating capacity and performance than R134a and R1234yf when the indoor temperature is -10° C and the compressor speed is 3000 rpm. R290 can provide higher heating capacity and performance than R134a and R1234yf. Poongavanam et al.[65] pointed out that there is a good consistency among R134a, R1234yf and R290, and proposed to use R290 and R134yf to replace R134a.

Much research has also been done on R290 heat pump systems. At -10° C, the heating capacity and COP of an R290 system increase by 55 per cent and 12.3 per cent respectively compared with an R134a system.[262] R290 is a flammable refrigerant. In order to improve the safety of the heat pump system, Huang Guangyan et al.[263] built an R290 heat pump system with a secondary heat exchange circuit, as shown in Figure 0-7. In a -25° C environment, the system's COP can reach 2.16, with very good heating performance. Aotecar also proposed a secondary circuit heat pump for electric vehicles, as shown in Figure 0-8. This system places the flammable R290 circuit in the front cabin, and controls the environment in the cabin by exchanging heat through the non-flammable secondary circuit. While realizing the modularization of the thermal management system, this also minimizes the charge of flammable refrigerants.[31] Jignesh K[264] built a set of test benches for electric vehicle air conditioning systems with heat regenerators, and tested R134a and R290. Under the conditions of a cooling capacity of 4kW, an evaporation temperature of 7.2°C, a condensation temperature of 55°C and a suction temperature of 35°C, compared with the R134a system, the discharge temperature of the R290 refrigeration system was reduced by about 2.1 per cent, and the compression ratio by about 17.9 per cent. The system's COP was reduced by about 2.4 per cent. It is therefore necessary to develop special compressors, heat exchangers, expansion valves and other components for the R290 system in order to achieve performance equivalent to that of the R134a system. Liu et al.[265] experimentally studied the effect of refrigerant charge on the performance of an R290 air conditioning system with different throttling devices. Their results showed that the system performance of the thermal expansion valve (TXV) or electronic expansion valve (EEV) had less dependence on refrigerant charge under overcharge conditions. In the case of insufficient charge, however, except without subcooling before the throttle device, the EEV system was less sensitive to the charge than the TXV system. Considering the application of TXV and EEV in air conditioners, therefore, a small amount of overcharging can improve the long-term performance of the system without sacrificing its short-term performance.

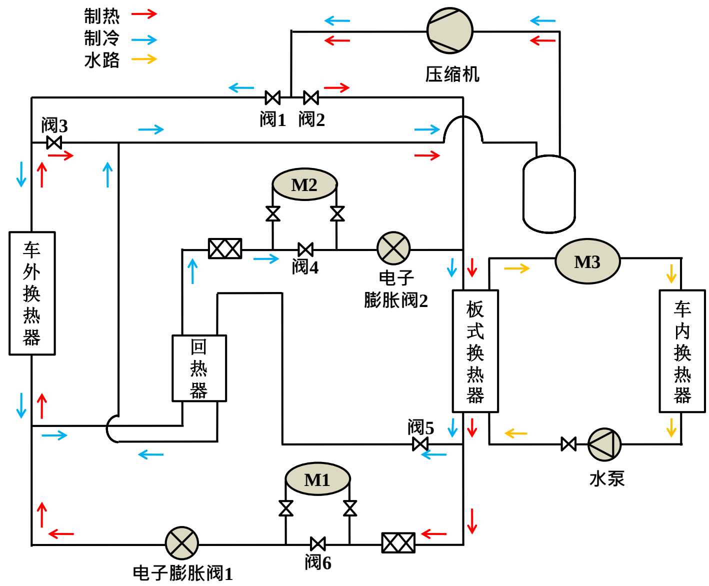
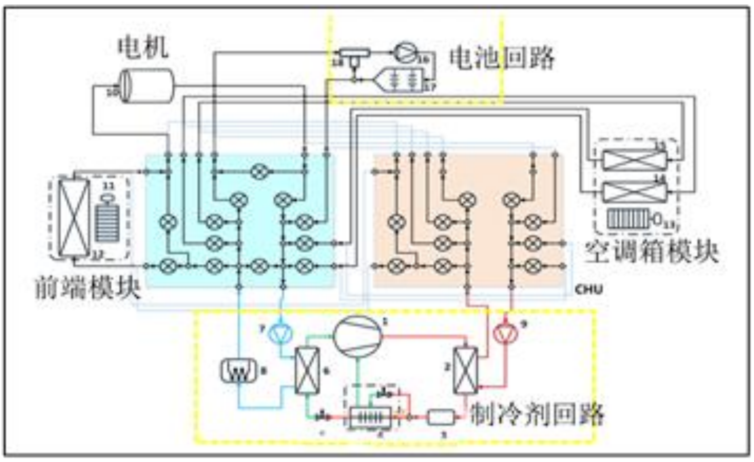
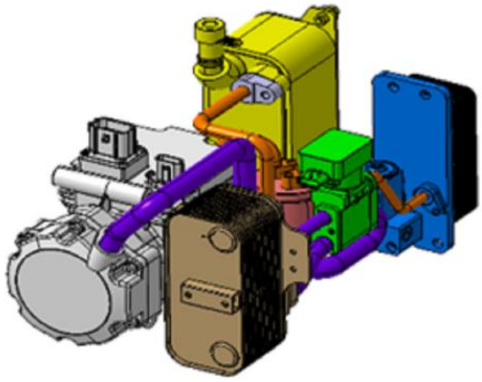


Figure 0-7 R290 heat pump system with secondary heat exchange circuit on the load side



(a) System process



(b) Full-scale system model

Figure 0-8 R290 secondary loop heat pump system

Comparison of R134a, R1234yf, R290 and R744 heat pump system performance

Here, the single-stage compression heat pump system with heat regenerator for the four working fluids of R134a, R1234yf, R290 and R744 was operated at the six ambient temperatures of 45° C, 35° C, 25° C, 0° C, -10° C and -20° C for performance comparison. Among these, the R290 system adopted the secondary cycle method to resolve its safety issues, as shown in the table below.

Table 2-18 Performance comparison of four working fluid systems under ambient temperature 45°C (full return air, cooling capacity requirement 5.75kW)

	R134a	**R1234yf**	**R744**	**R290**
Evaporation temperature (°C)	0	0	0	-3
Condensation temperature (°C)	63	63	/	65
Evaporation pressure (MPa)	0.29	0.32	3.49	0.43
Condensation/air cooling pressure (MPa)	1.80	1.76	11.00	2.34
Condensation/air cooling outlet temperature (°C)	50	50	50	50
Evaporator outlet temperature (°C)	5	5	5	5

Compressor suction temperature (°C)	25	25	25	22
High pressure outlet temperature of heat regenerator (°C)	38.23	37.35	45.12	38.11
Compressor displacement (cm^3/r)	34	34	6.8	34
Compressor frequency (Hz)	98	103	107	95
Cycle theoretical COP	3.47	3.38	1.93	3.09
Theoretical cooling capacity (kW)	6.39	6.42	6.40	6.81
Theoretical compressor power consumption (kW)	1.84	1.90	3.32	2.20
Compression efficiency	0.75	0.75	0.75	0.75
Heat transfer attenuation	10 per cent	10 per cent	10 per cent	15 per cent
Forecast cooling capacity (kW)	5.75	5.78	5.76	5.79
Predicted compression work (kW)	2.46	2.53	4.42	2.97
Air volume m^3/h	450	450	450	450
Power consumption of internal and external fans or pumps kW	0.5	0.5	0.5	0.58
Predicted system power consumption (kW)	2.96	3.03	4.92	3.55
Predictive system cooling COP	1.95	1.91	1.17	1.65

Table 2-19 Performance comparison of four working fluid systems under ambient temperature 35°C (full return air, cooling capacity requirement 4.23kW)

	R134a	R1234yf	R744	R290
Evaporation temperature (°C)	0	0	0	-3
Condensation temperature (°C)	55	55	/	57

Evaporation pressure (MPa)	0.29	0.32	3.49	0.43
Condensation/air cooling pressure (MPa)	1.49	1.46	10.00	1.99
Condensation/air cooling outlet temperature (°C)	40	40	40	40
Evaporator outlet temperature (°C)	5	5	5	5
Compressor suction temperature (°C)	25	25	25	22
High pressure outlet temperature of heat regenerator (°C)	27.79	26.85	33.77	27.54
Compressor displacement (cm^3/r)	34	34	6.8	34
Compressor frequency (Hz)	66	67	58	63
Cycle theoretical COP	4.27	4.24	2.90	3.79
Theoretical cooling capacity (kW)	4.74	4.69	4.73	4.99
Theoretical compressor power consumption (kW)	1.11	1.11	1.63	1.32
Compression efficiency	0.75	0.75	0.75	0.75
Heat transfer attenuation	10 per cent	10 per cent	10 per cent	15 per cent
Forecast cooling capacity (kW)	4.27	4.23	4.26	4.24
Predicted compression work (kW)	1.48	1.48	2.17	1.76
Air volume m^3/h	450	450	450	450
Power consumption of internal and external fans or pumps kW	0.5	0.5	0.5	0.56
Predicted system power consumption (kW)	1.98	1.88	2.67	2.32
Predictive system cooling COP	2.16	2.14	1.59	1.83

Table 2-20 Performance comparison of four working fluid systems under ambient temperature 25°C (fresh air, cooling capacity requirement 3.45kW)

	R134a	R1234yf	R744	R290
Evaporation temperature (°C)	0	0	0	-3
Condensation temperature (°C)	45	45	/	47
Evaporation pressure (MPa)	0.29	0.32	3.49	0.43
Condensation/air cooling pressure (MPa)	1.49	1.46	8.00	1.99
Condensation/air cooling outlet temperature (°C)	30	30	30	30
Evaporator outlet temperature (°C)	5	5	5	5
Compressor suction temperature (°C)	25	25	25	22
High pressure outlet temperature of heat regenerator (°C)	17.43	16.41	22.85	17.04
Compressor displacement (cm^3/r)	34	34	6.8	34
Compressor frequency (Hz)	50	50	40	48
Cycle theoretical COP	5.52	5.55	4.49	4.82
Theoretical cooling capacity (kW)	3.91	3.89	3.88	4.15
Theoretical compressor power consumption (kW)	0.71	0.70	0.86	0.86
Compression efficiency	0.75	0.75	0.75	0.75
Heat transfer attenuation	10 per cent	10 per cent	10 per cent	15 per cent
Forecast cooling capacity (kW)	3.52	3.50	3.49	3.53
Predicted compression work (kW)	0.95	0.93	1.15	1.15

Air volume m^3/h	450	450	450	450
Power consumption of internal and external fans or pumps kW	0.5	0.5	0.5	0.56
Predicted system power consumption (kW)	1.45	1.43	1.65	1.70
Predictive system cooling COP	2.44	2.44	2.11	2.08

From Tables 2-18, 2-19 and 2-20, it can be seen that as the summer temperature rises, the required cooling capacity increases, the refrigeration COP of the four working fluid systems increases and decreases with the ambient temperature, and the system's power consumption increases as the ambient temperature increases. The refrigeration performance of the R744 system is the worst among the four systems, which is due to the serious throttling loss at the expansion valve. Additionally, CO_2 systems operate at higher pressures than other systems, requiring optimization of system components. The cooling COP of the R1234yf heat pump system and R134a heat pump system are almost the same, and the cooling capacities obtained by the two are not much different. Compared with the R1234yf and R134a systems, there is still a certain gap in the cooling performance of the R290 system. It is therefore necessary to develop special components for the R290 system to improve its performance.

Table 2-21 Performance comparison of four working fluid systems under ambient temperature 0°C (fresh air, heating capacity requirement 3.79kW)

	R134a	**R1234yf**	**R744**	**R290**
Evaporation temperature (°C)	-5	-5	-5	-8
Condensation temperature (°C)	50	50	/	52
Evaporation pressure (MPa)	0.24	0.27	3.05	0.37
Condensation/air cooling pressure (MPa)	1.32	1.30	8.0	1.79

Condensation/air cooling outlet temperature (°C)	5	5	5	8
Evaporator outlet temperature (°C)	-2	-2	-2	-5
Compressor suction temperature (°C)	3	3	3	1
Compressor displacement (cm^3/r)	34	34	6.8	34
Compressor frequency (Hz)	46	46	29	39
Cycle theoretical COP	6.32	6.45	6.59	5.63
Theoretical heating capacity (kW)	4.22	4.26	4.25	4.51
Theoretical compressor power consumption (kW)	0.67	0.66	0.64	0.80
Compression efficiency	0.75	0.75	0.75	0.75
Heat transfer attenuation	10 per cent	10 per cent	10 per cent	15 per cent
Forecast heating capacity (kW)	3.80	3.84	3.82	3.84
Predicted compression work (kW)	0.89	0.88	0.86	1.07
Air volume m^3/h	300	300	300	300
Power consumption of internal and external fans or pumps kW	0.5	0.5	0.5	0.55
Predicted system power consumption (kW)	1.39	1.38	1.36	1.62
Predicted system heating COP	2.73	2.78	2.81	2.37

Table 2-22 Performance comparison of four working fluid systems under ambient temperature -10°C (30 per cent return air, heating capacity requirement 3.76kW)

	R134a	R1234yf	R744	R290
Evaporation temperature (°C)	-15	-15	-15	-18

Condensation temperature (°C)	50	50	/	52
Evaporation pressure (MPa)	0.16	0.18	2.29	0.26
Condensation/air cooling pressure (MPa)	1.32	1.30	8.0	1.79
Condensation/air cooling outlet temperature (°C)	35	35	9	37
Evaporator outlet temperature (°C)	-12	-12	-12	-15
Compressor suction temperature (°C)	8	8	-2	5
Compressor displacement (cm^3/r)	34	34	6.8	34
Compressor frequency (Hz)	79	79	39	63
Cycle theoretical COP	4.28	4.22	4.88	3.90
Theoretical heating capacity (kW)	4.19	4.19	4.25	4.48
Theoretical compressor power consumption (kW)	0.98	0.99	0.87	1.15
Compression efficiency	0.75	0.75	0.75	0.75
Heat transfer attenuation	10 per cent	10 per cent	10 per cent	15 per cent
Forecast heating capacity (kW)	3.77	3.77	3.82	3.81
Predicted compression work (kW)	1.30	1.32	1.16	1.53
Air volume m^3/h	300	300	300	300
Power consumption of internal and external fans or pumps kW	0.5	0.5	0.5	0.53
Predicted system power consumption (kW)	1.80	1.82	1.66	2.07
Predicted system heating COP	2.09	2.07	2.30	1.84

Table 2-23 Performance comparison of four working fluid systems under ambient

temperature -20°C (50 per cent return air, heating capacity requirement 3.79kW)

	R134a	R1234yf	R744	R290
Evaporation temperature (°C)	-25	-25	-25	-28
Condensation temperature (°C)	50	50	/	52
Evaporation pressure (MPa)	0.11	0.12	1.68	0.18
Condensation/air cooling pressure (MPa)	1.16	1.15	8	1.60
Condensation/air cooling outlet temperature (°C)	35	35	10	37
Evaporator outlet temperature (°C)	-22	-22	-22	-25
Compressor suction temperature (°C)	-2	-2	-2	-5
Compressor displacement (cm^3/r)	34	34	6.8	34
Compressor frequency (Hz)	118	116	51	88
Cycle theoretical COP	3.60	3.53	3.93	3.32
Theoretical heating capacity (kW)	4.22	4.22	4.25	4.50
Theoretical compressor power consumption (kW)	1.17	1.19	1.08	1.36
Compression efficiency	0.75	0.75	0.75	0.75
Heat transfer attenuation	10 per cent	10 per cent	10 per cent	15 per cent
Forecast heating capacity (kW)	3.80	3.79	3.82	3.82
Predicted compression work (kW)	1.56	1.59	1.44	1.81
Air volume m^3/h	300	300	300	300
Power consumption of internal and external fans or pumps kW	0.5	0.5	0.5	0.53

Predicted system power consumption (kW)	2.06	2.09	1.94	2.34
Predicted system heating COP	1.84	1.81	1.97	1.63

It can be seen from Tables 2-21, 2-22 and 2-23 that as the ambient temperature decreases in winter, the COP of the four working fluid systems decreases continuously with the ambient temperature, and the power consumption of the system increases accordingly. Under typical working conditions, the heating performance of the R744 system is better than that of the R1234yf and R134a systems, but the heating performance of the R290 system is slightly different from that of the R1234yf and R134a systems. Improving heating performance under typical working conditions is therefore key to the R290 system.

To sum up, the R744 and R290 systems have their own problems in cooling in summer and heating in winter. The R744 system has poor cooling performance at high temperatures. The R290 system itself has certain safety issues. The performance of R1234yf, however, is basically the same as that of R134a under the four working conditions compared, and it is better than the R744 and R290systems under typical working conditions. The replacement of R134a by R1234yf is the option with the least impact on the industry. In terms of safety, the ASHRAE safety level of R1234yf is A2L, non-toxic and weakly flammable. Years of research by the American Society of Automobile Engineers (SAE) have shown that R1234yf is not flammable in the working environment of automotive air conditioners and enjoys the same level of safety as R134a. R290, however, possesses a certain degree of flammability and combustability. The safety of the R290 system, therefore, also needs to be considered. In terms of system cost, the thermal performance of R1234yf is similar to that of R134a. In the heat pump system performance test, the results[24] show that the difference is only 2 – 4 per cent. In air conditioning systems using R134a as the refrigerant, therefore, the direct substitution of R1234yf for R134a can be implemented, which effectively saves on the research and development costs of the system. R744, however, has a high operating pressure and high system costs. It also requires the design of a special heat pump system and thermal management structure, as well as independent research and development of related components; research and development investment is relatively high. In terms of commercialization, most of the newly designed models currently sold in the EU and the United States use R1234yf as the refrigerant. In China, NIO Inc. and Volvo became the first vehicle companies to use R1234yf refrigerant, which shows that R1234yf has an excellent advantage in terms of commercial popularity.

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