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R744 heat pump solutions for electric vehicles

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ABSTRACT

With the shift from the combustion engine to the electric motor, thermal management system is taking on a new significance in the automotive industry. Optimal temperature control of the individual components and air conditioning of the vehicle cabin must be implemented as efficiently as possible to achieve a high driving range and a safe operation of the electric vehicle (EV). With the acceptance of the restriction of PFASs, R744 would be the only, not flammable refrigerant that can be considered for environmentally compatible use in EV heat pumps. A literature review showed the very high potential of R744 heat pump systems for this application. Because of the different properties of R744 compared to the common refrigerants, further investigations are needed to determine suitable system design, operation, and control strategies for R744 heat pump systems in the context of the EVs.

Keywords: Carbon Dioxide, heat pump, vehicle thermal management, electric vehicles

1. INTRODUCTION

The environmental compatibility of halogenated refrigerants has been in question since the 1980s. Chlorofluorocarbons (CFCs), which damages the ozone layer, have now been replaced by halogen-free hydrocarbons in some applications worldwide (UBA, 2017). In other applications, hydrofluorocarbons (HFCs) have been introduced for CFCs. Since these substances are harmful to the climate, they have often been replaced since the 2010s by unsaturated HFCs (Hydrofluoroolefins -HFOs) with claim to have a lower climate impact. To replace the climate-damaging HFC-134a (R134a) in automotive air conditioning systems, the European automotive industry has been developing innovative systems using the natural refrigerant carbon dioxide (R744) from the late 1990s on. Since 2006, studies for series production have begun. However, the switch to the refrigerant R744 was abruptly halted in Europe in 2010 as the international automotive industry finally agreed on the halogenated refrigerant HFO-1234yf (R1234yf). (UBA, 2021)

R1234yf was developed to replace the refrigerant R134a in existing automotive air conditioning systems as well as for use in new types of vehicles. Its global warming potential of 4 is significantly lower than that of R134a. (Deutsche Umwelthilfe e.V., 2012) What both refrigerants have in common is that Trifluoracetat (TFA) is formed during atmospheric degradation. Due to its high water solubility and mobility, TFA easily enters the water cycle and spreads through it in the environment. Because TFA is not degradable, i.e. very persistent, it remains in the environment after its entry. In case of increased TFA concentrations in groundwater and soil, potential risks to humans and the environment may result. R134a is very stable in the atmosphere and is converted slowly over many years to about 7 % to 20 % TFA, while R1234yf is degraded to over 99 % TFA within a few days. (UBA, 2021) In a study by Behringer et al. (2021), the TFA formation potential by refrigerant emissions could further triple by 2050 caused by the switch from R134a to R1234yf. In addition, further risks occur due to the high flammability of R1234yf. In the year of 2012 Daimler found that in the case of leakages, the refrigerant can ignite in the engine compartment and release corrosive hydrofluoric acid. As a result, Daimler deemed R1234yf as too dangerous and recalled hundreds of cars. (ntv, 2013) In February 2023 a proposal for a restriction of per- and polyfluoroalkyl substances (PFASs) has been submitted by five European countries, including Germany, the Netherlands, Sweden, Norway, and Denmark. If accepted, the proposal would enter into force in 2025 with an 18-month transition period to alternatives. (ECHA, 2023) R1234yf, which falls within the definition of PFASs, wouldn't be longer acceptable in the automotive sector on a legal level.

Due to the uncertainties arising from the use of synthetic refrigerants, R744 is becoming attractive again in the international automotive industry. This paper gives an overview of the current state of the art of R744 heat pump solutions for application in EV. In the first part, an introduction to the thermal management of EVs is given with regard to the vehicle cabin and battery heating and cooling requirements. Then the current research results as well as the market available R744 heat pump systems in EV are discussed. In addition, further potential system improvements are presented. By doing so, it should become clear, how the advantages of R744 as a refrigerant can be used most effectively, and how weaknesses could be overcome in the context of EV thermal management.

2. R744 REFRIGERATION IN THE CONTENT OF EV

2.1. Thermal management system in battery electric vehicles

Thermal management generally involves the control of the heat flow in a system. It aims to the optimal temperature control of the individual components in order to optimize their performance as well as to minimize their energy consumption. In the EV the areas of action of the thermal management are the temperature control of the vehicle cabin and the battery as well as the cooling of the engine and the power electronics (powertrain, PWT). Though to the thermal influences of the environment as well as the heat gains from the vehicle occupants and the individual system components, heating and cooling capacity must be provided to meet the required comfort and operating temperature. (Tschoeke, 2015)

2.1.1. Requirements for cabin thermal management

The thermal management of the vehicle cabin aims to create a comfortable climate in the interior of the vehicle. Furthermore, it ensures vehicle safety by lowering the CO_2 concentration in the cabin and guaranteeing good visibility for the vehicle drivers. The DIN 1946-3 (Deutsches Institut für Normung, 2006) formulates requirements for vehicle air conditioning. Accordingly, the air temperature and the speed of the air flowing into the vehicle perceived as comfortable vary depending on the outside temperature and the solar radiation. Apart from that an average temperature of 20 °C in heating mode and 25 °C in cooling mode must be reached within 30 minutes in outside air mode. To prevent the windows from fogging or icing, a maximum permissible water vapor content of 13 g/kg must be observed. The relative humidity should be between 30 % and 60 %. In accordance with the requirements of the vehicle cabin, the air conditioning unit is responsible for temperature control, dehumidification of the air mass flow, and its distribution in the vehicle cabin. Due to the characteristics of the vehicle envelope, such as large window areas and a high heat transfer coefficient, the air conditioning system in the vehicle is designed primarily for transient operation. Compared to the building sector, therefore, significantly higher heating and cooling capacities are required in relation to the surface. (Grossmann et al. 2020)

In contrast to vehicles powered by internal combustion engines, significantly less waste heat is generated in the more efficient electrical motor of EVs. To provide heat for the cabin, heat pumps or electric heaters are typically required. They represent an additional consumer, which can have a significant impact on the driving range, especially at low outside temperatures. In comparison, the provision of heat and cold for cabin air conditioning takes on a new significance in EVs. To maximize the driving range, new ways must be found to use heat sources and heat sinks as efficiently as possible. (Flieger, 2014)

2.1.2. Requirements for battery thermal management

The operating temperature of the battery system defines its performance, aging, and operational safety. The performance of the battery system is determined by the internal resistance of the battery cells and the current flowing through the cell. With increasing current and increasing internal resistance, cell losses increase, resulting in a conversion of electrical energy into heat. However, the internal resistance of the cell decreases with increasing temperature. In order to guarantee high performance of the battery system, a defined operating temperature should therefore be provided by the thermal management system. (Gantenbein, 2019)

The maximum and minimum range of operating temperature is limited by the aging mechanisms of the cell occurring during operation. Lithium plating is of particular importance for the thermal management of the EV. It occurs during the charging of the cell at low temperatures and/or high currents and can cause irreversible damage to the cell structure. This results in a reduction of the cell capacity and, in the worst case, can lead to a short circuit. In addition, the aging mechanisms can also be intensified by high operating temperatures of the cell. An example of this is the degradation of the cathode and the accelerated growth of the SEI (solid electrolyte interphase)-layer at the anode, which leads to a reduction of the capacity and an increase in internal resistance. For a detailed explanation of the aging mechanisms and their effects on cell properties, please refer to Alipour et al. (2020) or Gantenbein (2019).

Furthermore, the temperature has an influence on the safe operation of the battery cell. At high operating temperatures the probability of a thermal runaway increase. This self-reinforcing exothermic reaction releases a large amount of heat and, in the worst case, can cause the cell to ignite. High temperatures in the cell can occur in particular when high charge or discharge currents flow. (Gantenbein, 2019)

In order to guarantee high performance and minimal risk of aging and safety issues of the battery system, a defined operating temperature should therefore be provided by the thermal management system. To achieve the optimum operating temperature, a compromise must be found between heat losses due to the internal resistance of the cell or rather cell aging and the heating energy input, under which the driving range reaches the most favourable values possible. Reference values for the optimum temperature range can be found in the literature. For lithium-ion batteries, the optimum temperature range lies between 20 °C and 40 °C. (Korthauer, 2013)

In addition, the thermal management of the battery system must ensure that the temperature of the individual cells is as homogeneous as possible. This enables uniform aging and consequently a uniform decrease in the capacity of the individual cells. In this way, the effort for balancing can be kept low. As a result, the temperature difference between the medium entering the battery cooling plate and the average battery cell temperature should be controlled accordingly. (Alipour et al. 2020)

2.1.3. Integrated thermal management system

The thermal management of the vehicle cabin, the battery system, and the PWT have different thermal requirements with regard to the temporal occurrence of the heat demand as well as the required operating temperature. The approach of the integrated thermal management system is to couple the different consumers and generators of thermal energy via a central refrigerant circuit, so that the respective heat flows are introduced into the system as profitably as possible. On the one hand, this is advantageous in terms of reducing the number of components required, which is accompanied by a reduction in weight and installation space in the vehicle. Secondly, the overall efficiency of the system can be significantly increased by incorporating the waste heat from the battery, the power electronics, or the electric motor into the system. One challenge of this approach is the potentially very complex system design and control concept. Heat pumps are well suited for the provision of hot and cold in the integrated thermal management system. In comparison to electrical heaters, the heat pump reaches a generally higher system efficiency. Also, the advantages of simultaneous process control by integrating the waste heat can further contribute to increasing efficiency. (Liang, 2021) To illustrate how the battery can be integrated into the heat pump process three typical methods are presented in figure 1: air cooling, direct cooling with refrigerant, and indirect cooling with coolant.

The air-cooled system represents the most simple concept and can be seen in figure 1(a). Via the battery evaporator, heat is transferred from the refrigerant circuit to the airflow, which in turn transfers the heat to the battery cells. Disadvantages are the additional weight and the installation space of the fan and its noise. Also, the lower heat transfer properties of air are not favourable for high capacities, e.g. during fast charging.

Indirect battery cooling with a secondary coolant circuit is shown in figure 1(c). Heat can be transferred from the coolant circuit to the secondary circuit via the so-called chiller. Depending on the outside air temperature, it is also possible to switch between the operation of the chiller and the radiator, thus reducing the operating time of the compressor. In both cases, the heat transfer from the coolant circuit to the battery occurs in the cooling plate. As a result, this method of battery temperature control proves to be more energy-efficient and flexible compared to temperature control with air. Heat transfer by means of a cooling plate makes it possible to supply and dissipate larger amounts of heat from the battery. However, the disadvantages are the higher complexity as well as the high space requirement, and the additional weight of the chiller, coolant pump, and additional lines for the secondary circuit. (Kortenhauer, 2013)

In Figure 1 (b) the direct cooling with refrigerant can be seen. Both the temperature control of the vehicle cabin and of the battery is carried out via the refrigerant circuit. The heat to the battery is transferred also via a cooling plate, through which the refrigerant flows directly. This is advantageous in terms of the reduction in components and consequently in weight and installation space. Additionally, the losses of the heat transfer between the refrigerant and the secondary circuit can be avoided and the latent heat transfer of the refrigerant to the battery enables greater performance compared to the sensible heat transfer in the secondary circuit. In addition, since latent heat transfer is isothermal, the temperature difference between the battery cells can be reduced by this method. In total, this leads to a higher heat transfer efficiency and a more uniform temperature distribution in the battery system. (Wang, 2022)

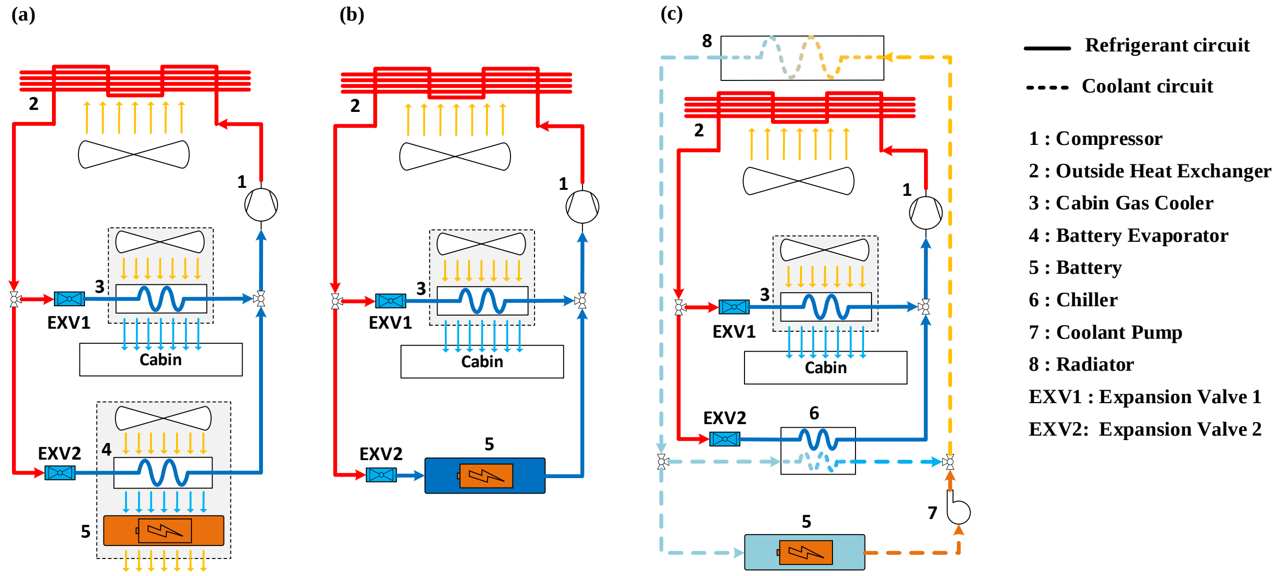


Figure 1: Typical heat pump systems in EVs for cabin and battery cooling (not all components included)

2.2 State of the art description of R744 heat pump solutions for EV

2.2.1 Typical thermal management systems available in the automotive market

Figure 2 shows an exemplary R744 heat pump system which demonstrates the state of the art of currently available systems in the automotive market. Shown is the heating mode. The system architecture follows the approach of indirect battery cooling with a secondary coolant circuit (figure 1(c)). The refrigerant circuit is made up of the following main common components: an E-compressor, an evaporator, a gas cooler/condenser, an outdoor heat exchanger (OHX), electronic expansion valves (EXV), shut-off valves (SOV), an accumulator, an internal heat exchanger (IHX), and a chiller. By changing the refrigerant flow direction through the SOVs the system can fulfill cabin and battery cooling, cabin heating, and cabin dehumidification. In the coolant circuit, the architecture includes the battery system, the electric drivetrain, two coolant pumps, a radiator, a high-voltage battery heater, and four mixing valves. The coolant circuit can operate in two loops: one for the electric drivetrain and one for the battery. As these loops can work independently or can be interconnected, the system becomes quite flexible in terms of providing heating and cooling capacity through the radiator, the high-voltage heater, or the chiller in the coolant circuit. The absorbed heat at the chiller can be used in the refrigerant circuit to provide a higher temperature at the suction side of the compressor. By doing so higher efficiency can be achieved. In heating mode, the two heat exchangers in the HVAC (the cabin gas cooler and the evaporator) are arranged in series to increase the heat transfer surface. The battery is only heated by the high-voltage battery heater.

The ADAC (2022) evaluated the thermal management systems of different current available EVs by test bench measurements. Especially at low outside temperatures and short driving distances, the R744 heat pump system showed a significantly higher energy consumption of the thermal management system compared to other EVs. At an outside temperature of -7 °C compared to an outside temperature of 14 °C, the overall energy consumption of the vehicle almost doubles. Comparable vehicles using other refrigerants showed an increase in energy consumption of around 60%. These results indicate that further improvements of the R744 system, whether in system architecture or control strategy, are needed to be competitive with other refrigerants.

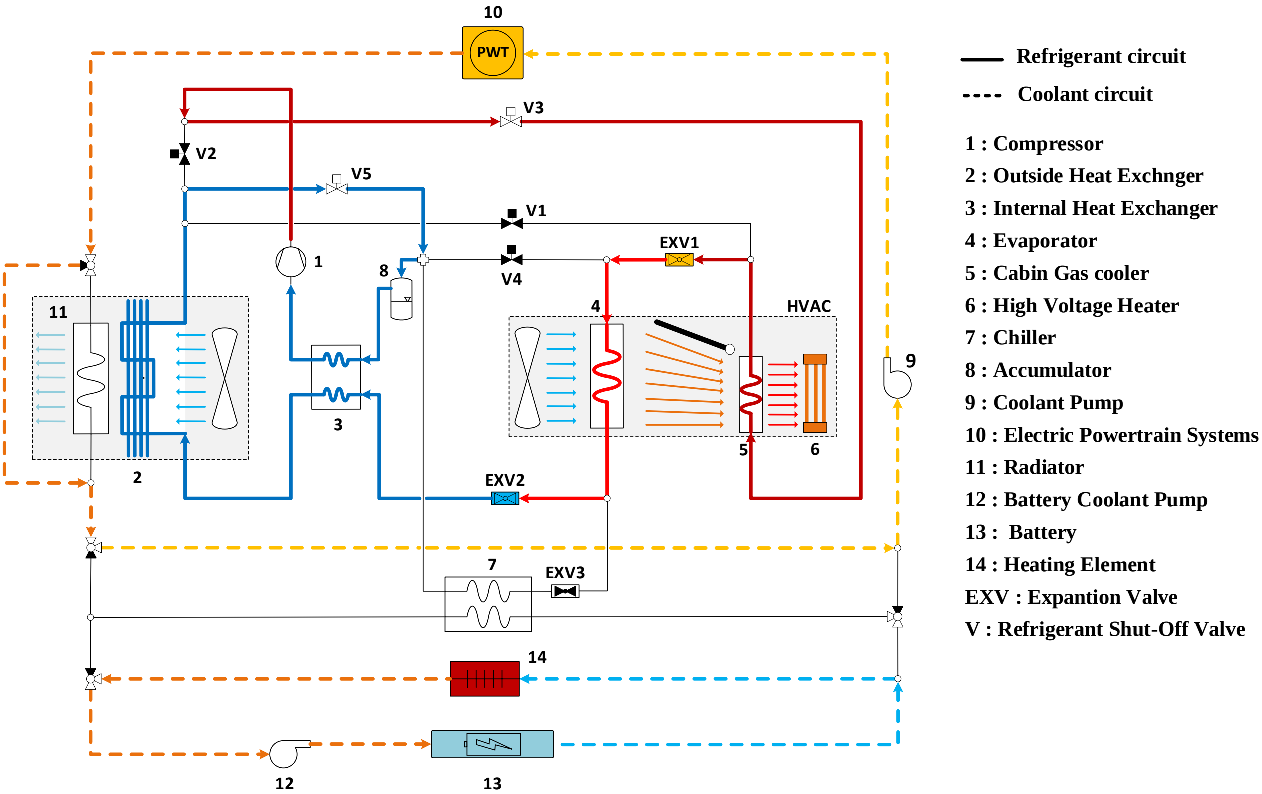
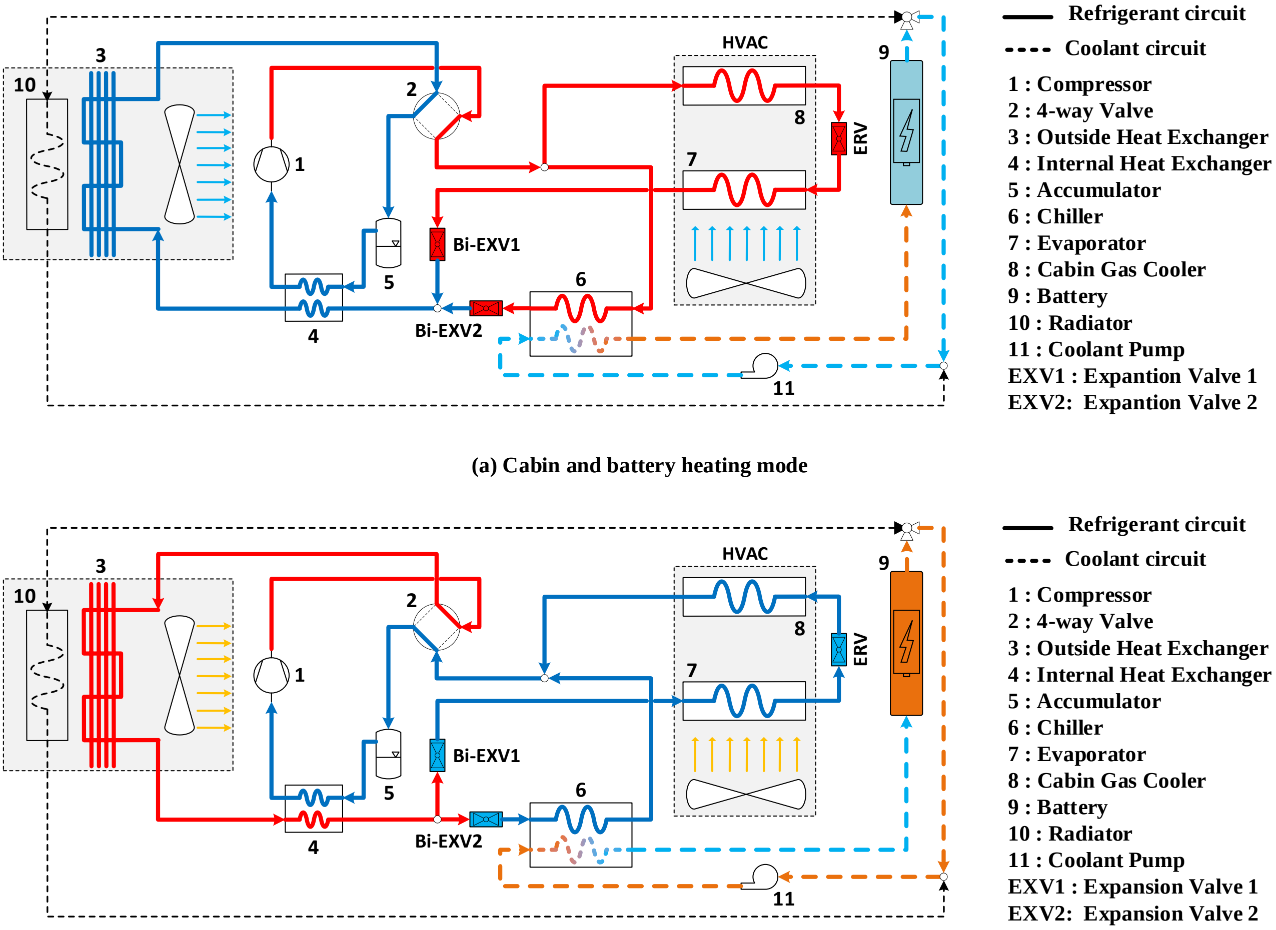


Figure 2: Exemplary demonstration of the state of the art of currently available R744 heat pump system in the automotive market

2.2.2 Review of the current literature

Wang et al. (2021) did an experimental comparison of R744 and R134a heat pump systems for EV. Figure 2 shows the architecture of the R744 system for the cabin and battery heating (figure 3 (a)) and cooling (figure 3(b)) mode. The refrigerant circuit also follows the approach of indirect battery cooling with a secondary coolant circuit, similar to the before-mentioned system. Instead of the SOVs, a 4-way valve is used to change the refrigerant flow direction according to the different modes. In addition, both heat exchangers in the HVAC are not only used in series in heating mode but also in the cooling mode for increasing the heat transfer surface. On the coolant side, battery heating is provided by the refrigerant circuit without using an additional electric heater. For cabin heating and cooling the performance of the R134a and R744 systems have been compared from 15 °C to 45 °C for cabin cooling and at −15 °C, −10 °C and −5 °C for cabin heating. First, the heating and cooling capacity of the two systems were compared for the same compressor speed and then the COP of the system is compared, keeping the cooling/heating capacity identical. In cooling mode, the R744 system can reach a similar COP with the same cooling capacity compared to the R134a system. Here, the insufficient cooling performance of R744 caused by the thermodynamic properties can be compensated by the larger heat transfer area due to the two heat exchangers in series in the HVAC unit. At low compressor speed, the R744 system shows a smaller COP. Wang et al. attributed this to the poor compressor performance. Improving the volumetric and isentropic efficiency, especially at low-load working conditions is still challenging for R744 compressors. In heating mode, the results showed that the performance of the R744 system is significantly better compared to the R134a system. Because of the higher suction vapor density of R744 at a lower temperature, the compressor can run at a lower speed to obtain the same heating capacity as with R134a. Due to the power reduction, the R744 can provide a larger amount of heat with higher COP. In contrast, the R134a system is unable to realize the battery heating function using the air source heat pump and the PTC is mandatory as an auxiliary heater. Wang et al. draw attention to the problem that many current commercially available EVs adapt to the R134a system for heating in winter, by taking electric heaters as an auxiliary, which largely reduces the driving range of EVs because of their low efficiency moreover they are high in component costs. Based on the test results they propose a novel R744 system that has a simple structure with fewer components and the two heat exchangers in series in the HVAC to provide a larger heat transfer area.



(b) Cabin and battery cooling mode

Figure 3: Schematic R744 heat pump system for EV from Wang et al. (2021)

Chen et al. (2021) investigated an R744 system for EV in heating mode at ambient temperatures from 0 °C to -20° C. It was pointed out, that at extreme outdoor temperatures, high discharge temperatures occur, which could be challenging for components tolerance. A concept of two-stage compression with intermediate cooling was introduced. The results showed, that the system can reduce the discharge temperature effectively so that the heating performance compared to the system without two-stage compression could be significantly improved in terms of heating capacity and COP. The advantages get more significant as the ambient temperature decreases.

The defrosting strategies in EV were studied by Wang et al. (2023). It was shown that traditional defrosting strategies would lead to various false defrosting phenomena and even damage to the compressor and pipes in the application of EV. The defrosting control logic of conventional heat pumps cannot be applied directly to EV because of their more complex operating conditions and control strategies. A new defrosting strategy was proposed for EV. The maximum discharge temperature was taken as the new criterion for the defrosting control. Hence, the performance of the defrosting in EV could be verified.

Wang et al. (2023) evaluated the performance of the battery thermal management with two-phase refrigerant direct cooling (figure 1 (b)). A parallel thermal management model for the battery and the cabin was used. For evaluating the battery thermal management, the main criteria were the battery temperature and its uniformity temperature difference. They were regulated by the evaporation temperature and vapor quality in the cold plate. The results show that the parallel direct cooling of the battery and cabin with R744 as a working fluid can manage the surface temperature and uniformity of the battery. It was found that for different battery heating power, there is an optimal battery cooling evaporation temperature. In general, the COP is reduced with increasing battery cooling capacity and increasing evaporation temperature. Wang et al. consider a battery cooling capacity from 0.2 kW to 0.8 kW. In order to demonstrate the advantages of the two-phase refrigerant direct battery cooling when using R744 as a refrigerant, further investigation should be conducted for higher battery cooling capacities.

In summary, based on the state of the art described above, it can be stated that the refrigerant R744 is suitable for use in EVs. In heating mode, R744 has a decisive advantage compared to R1234yf or R134a. Especially at temperatures below 0 °C, the R744 system shows a higher efficiency due to the higher suction vapor density. Additionally, no auxiliary heater is necessary, which further increases the efficiency and reduced the system by a highly expensive component. This condition has been sufficiently studied in the literature. The coverage of the cooling demand takes a new significance in the EV regarding battery performance and safety. In reviewed studies, the cooling capacity was considered with a maximum of 4 kW or wasn't considered at all. Regarding the further increase of charge and discharge power of the battery (e.g., during fast charging), research is needed to evaluate the system under these conditions. The use of both heat exchangers in the HVAC (gas cooler and evaporator) seems promising to increase the cooling/heating capacity. Additionally, the literature reviewed indicates that traditional thermal management solutions which suit other refrigerants or vehicle types are typically adopted for R744 systems. Due to the different properties of R744, these are often not suitable and lead to inefficient and unsafe operating conditions. Further investigations are needed to determine suitable system design, operation, and control strategies for R744 heat pump systems in the context of EV.

3. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this study, the main requirements for the thermal management of battery electric vehicles were presented and a literature review of the current state of the art R744 heat pump solutions was carried out. It could be obtained that the R744 is a promising refrigerant in the application of the thermal management of EVs. To become competitive with the common refrigerants, further efficiency-improving measures are necessary. A general challenge is the fact that the properties of R744 differ significantly from established refrigerants, which is why methods that have proven successful in the past cannot necessarily be applied to the R744 system. The reviewed literature listed improvements in the system architecture or control strategies, which give an idea of the great potential of the refrigerant. For future work, more effort should be made to adapt the process design and operating strategies specifically to the properties of R744 to reach even higher performances. The higher heat rejection and throttling losses of R744 compared to other refrigerants could provide potential opportunities for efficiency improvements, such as expansion work recovery with ejectors.

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