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REVIEW

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Advances and challenges of R744 based thermal management systems in electric vehicles

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Abstract
The global transition to electric vehicles is essential for reducing transportation-related carbon emissions. Despite this, the limited driving range, primarily caused by the high energy consumption of thermal management systems, remains a significant barrier to the widespread adoption of EVs. Concurrently, international regulations are phasing out conventional refrigerants with high global warming potential, leading to the use of natural refrigerants, such as carbon dioxide (R744). R744 meets environmental standards and exhibits favorable thermodynamic performance. The current state of R744-based thermal management in EVs advancements in transcritical R744 heat pumps technologies, operational challenges and optimization strategies were comprehensively reviewed in this work. The review also included an overview of the present landscape and prospects for R744-based TMS in next-generation electric vehicles. It could be concluded that future thermal management strategies of EVs can be based on integrated R744-based solutions, featuring further advanced add-ons, such as AI-based control strategies.

Keywords Air conditioning, Carbon dioxide, Cooling, Heating, Heat pump, Electric vehicle, Thermal management system

1 Introduction

The transportation sector is experiencing a significant transformation, primarily driven by environmental regulations and the imperative to mitigate climate change. This transition involves a shift from fossil fuel-powered vehicles and traditional internal combustion engines (ICEs), to electric vehicles (EVs) [1]. Battery electric vehicles (BEVs) are widely regarded as the ultimate solution, providing low emissions and the potential for a reduced carbon footprint [2]. Nevertheless range anxiety continues to impede widespread adoption, largely due to the substantial energy consumption with the Heating, Ventilation, and Air Conditioning (HVAC) system identified as a major contributor [3–5]. The Thermal Management System (TMS) in electric vehicles is inherently complex, serving to maintain passenger comfort and safeguard powertrain components for reliable operation [4, 6]. In contrast to ICEs, which utilize abundant waste heat for heating, EVs must source this heat from the battery pack. In cold climates, this results in a substantial thermal load, often necessitating the use of inefficient positive temperature coefficient (PTC) heaters [7]. Consequently, vehicle range can decrease by up to 50% during severe winter conditions [8].The TMS is also responsible for maintaining optimal temperatures for the battery and power electronics, as lithium-ion batteries perform best within the 15 °C to 35 °C range [4]. Deviations from this range accelerate degradation, reduce performance, compromise safety, and shorten battery lifespan [9]. Therefore, the TMS must provide cooling during periods of high demand or fast charging and supply heating in cold environments to ensure both performance and longevity. Addressing these diverse requirements with limited battery energy constitutes a central design challenge for BEVs.

Battery thermal management (BTM) is a key part of the TMS in EVs. It is responsible for heating and cooling the battery to maintain optimal performance and safety. Conventional cooling methods are grouped by the cooling medium used, such as air, liquids, phase change materials (PCMs), or heat pipes. The complexity, efficiency, and suitability of each method depend on the vehicle's design and working conditions. Recent review studies have explored advanced heating and cooling strategies, including new technologies [10, 11]. These systems are also divided by working-fluid configuration: direct or indirect. The degree of integration between HVAC and BTM components is also considered. This classification method aligns with the Integrated thermal management systems (ITMS) approach, which aims to improve energy efficiency, reduce redundant components, and enhance system performance through careful design and control.

This challenge has driven the development of highly efficient heating and cooling solutions, notably Heat Pump (HP) systems, which are a critical research focus for extending EV range and improving practicality across diverse climates [12], as summarized in Table 1.

Alongside transportation electrification is a regulatory shift in HVAC and refrigeration. International agreements, such as the Montreal Protocol and Kigali Amendment, are eliminating high-impact refrigerants [17, 18]. The focus has gone from phasing out ozone-depleting substances—like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)—to HFCs, for example R134a, due to high GWP [19, 20], and HFOs, like R1234yf for PFAS issues. R134a remains widely used, while R1234yf is currently the car industry's preferred choice.

Natural refrigerants are increasingly recognized as sustainable alternatives, offering zero ODP, negligible GWP and no PFAS emissions [18, 21]. R744, is a promising candidate for mobile applications [22, 23], as it is non-toxic, non-flammable, cost-effective, and widely available [24, 25]. R744 possesses favorable thermophysical properties, including high volumetric cooling capacity and excellent heat transfer characteristics, which facilitate compact components design [26]. The adoption of R744 in EV thermal management extends beyond environmental compliance, representing a technical strategy to address the limitations of electric mobility. It's characteristics enable heat pump to operate efficiently for heating, even at low ambient temperatures where conventional systems are ineffective and PTC heaters are typically required [14, 27, 28]. Enhanced cold-weather performance mitigates winter range loss in EVs. Therefore, R744 offers both robust environmental benefits and high-performance heating that supports extended EV range.

Table 1 Comparative analysis of primary EV heating technologies [13–16]

Technology	Heating mechanism	Typical COP[a]	Impact on driving range	Environmental footprint	Key advantages	Key disadvantages
PTC heater	Electric resistance	COP ≈ 1	Severe reduction; especially in cold climates	Low direct impact (uses grid electricity); high indirect impact due to inefficiency	Simple, low-cost, fast response, reliable heating capacity	Extremely inefficient, high battery drain, significant range penalty
HFC[b]- HFO[c]-based HP (e.g., R134a, R1234yf)	Vapor Compression Cycle (VCC)	COP > 1, but performance degrades sharply at low ambient temperatures (e.g., COP ≈ 1.5 – 2.0 at – 10∘C)	Moderate reduction: better than PTC but cannot be used at low temperatures	R134a: High GWP (~ 1430); R1234yf: Very low GWP (< 1), but both classified as PFAS[d]	More efficient than PTC, mature technology, good cooling performance	Not usable at low temperatures, usually require PTC-backup; HFCs have high GWP[e]
R744 HP	Transcritical VCC	COP > 1, maintains high efficiency at very low ambient temperatures	Minimal reduction; significantly better than PTC and HFC/HFO systems in cold climates	GWP = 1, ODP[f] = 0, no PFAS issues	Excellent heating performance in extreme cold, environmentally benign, rapid heating, potential for waste heat integration, no need for PTC heaters	Lower cooling efficiency in high ambient temperatures, high operating pressures require robust components, more complex system control

[a] Coefficient of performance (COP); [b] hydrofluorocarbons (HFC); [c] hydrofluoroolefins (HFO); [d] polyfluorinated alkyl substances (PFAS); [e] global warming potential (GWP); [f] ozone depletion potential (ODP).

Previous reviews have considered EV thermal management and transcritical CO_2 cycle as separate topics. Table 2 summarizes selected publications from the past decade. Reviews by Zhang et al. [8], Liang et al. [29], and Lei et al. [6] investigated the integration of battery thermal management and TMS in EVs, but did not examine the use of R744 as a refrigerant. Qi [12] and Zhang et al. [11] explored heating and cooling strategies, including vapor compression and non-conventional cycles, but concentrated on alternative refrigerants rather than R744. Ko and Jeong [30] assessed HFOs and natural refrigerants, such as propane (R290), in vapor-compression cycles, but did not include R744. Yu et al. [26] reviewed advances in modified transcritical cycle technologies using R744 and refrigerant blends, but the primary focus was not on EVs, although automotive applications were discussed. Ji et al. [31] conducted the only study that analyzed transcritical cycles using R744 in automobiles, including EVs, but did not address the integration of air conditioning/heat pump systems (ACHP) with the vehicle TMS. More recently, Mohaideen et al. [32] presented a comprehensive review of R744 HP applications in EVs, although this analysis was specifically limited to vapor injection (VI) technologies.

This review addresses the identified gap by providing an updated overview of R744 heat pump technology for EVs, emphasizing integration with BTM and TMS, and discussing challenges and future research directions. The manuscript is organized as follows: Sect. 2 provides a comparison of current enhancement technologies for R744 HPs

Table 2 Research reviews about ACHP/TMS in EVs

Author	Primary topic	Focus on R744	System	Focus on EV application
Lei et al. [6]	General solutions for TMS	No	Separate and integrated TMS	Yes
Zhang et al. [8]	General solutions	No. Includes HFCs and natural refrigerants	ACHP + TMS. Includes non-VCC systems	Yes
Zhang et al. [11]	HP integrated energy systems	No	ITMS	Yes
Qi [12]	General advances in ACHP technology	No. Includes R744, R134a and other alternatives	ACHP. Includes non-VCC systems	Yes
Yu et al. [26]	Modified transcritical CO_2 cycles	Yes. Also includes CO_2-blends	Transcritical cycles	No. Includes automotive, commercial, residential applications
Liang et al. [29]	Advances and challenges on TMS	No	ITMS	Yes
Ko and Jeong [30]	Current technologies and challenges	No. Includes HFCs, HFOs and natural refrigerants	VCC-ACHP	Yes
Ji et al. [31]	General improvements in transcritical cycles and control methods	No	Transcritical ACHP. Without depth in TMS	Yes
Mohaideen Abdul Khader et al. [32]	Current state of VI in HP	Yes	VI HP	Yes

and other refrigerants. Section 3 examines integrated systems that connect R744 heat pumps with EVs. Section 4 discusses operational challenges and optimization strategies for EV-HPs. Section 5 reviews component-level innovations and constraints. Section 6 presents future research directions, identifies remaining literature gaps, and offers conclusions.

2 Performance enhancement technologies for R744 ACHP systems

The basic transcritical R744 vapor compression cycle inherent thermodynamic inefficiencies. To address these challenges, researchers have developed various cycle modifications to enhance system performance. Typically, these enhancement technologies are classified by their primary function, such as increasing subcooling, rising low temperature heating capacity, recovering expansion work, and improving heat exchanger architectures.

2.1 Subcooling increment via Internal heat exchanger (IHX)

A key and widely used modification in transcritical R744 cycles is the internal heat exchanger, or suction-line heat exchanger, which transfers heat between high-pressure R744 leaving the gas cooler and low-pressure vapor R744 leaving the evaporator before entering the compressor [33].

The IHX cools high-pressure R744, reducing its specific enthalpy before expansion. This added subcooling shifts the expansion starting point of the pressure-enthalpy ($P-h$) diagram (see Fig. 1), resulting in a greater heating effect. In cooling mode, the IHX lowers R744 quality after expansion, which increases the specific refrigeration effect

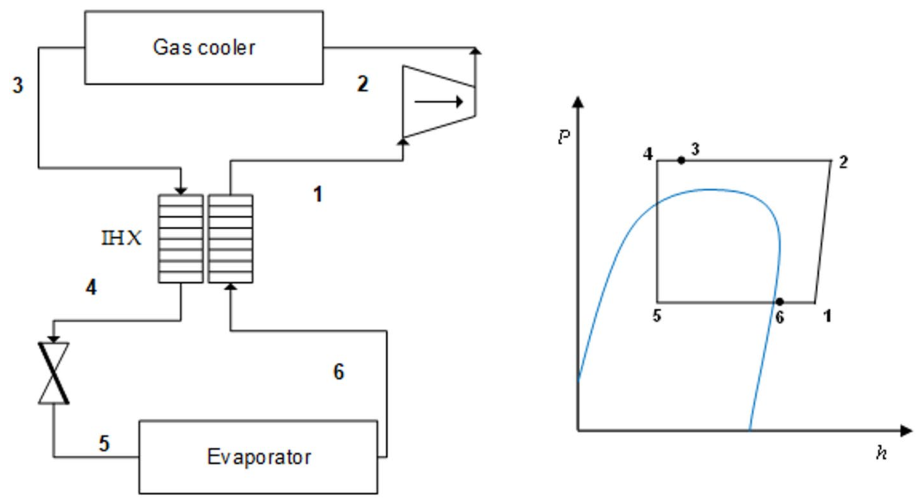

Fig. 1 P-h diagram and schematics of transcritical R744 with IHX

in the evaporator and decreases exergy destruction in the expansion valve. However, the benefits of the IHX are dependent of the application [26, 34, 35].

Experimental data showed that a R744 system with an IHX can increase its efficiency up to 25% [33]. Other studies report COP enhancements of 14.5% to 18.5% under different ambient conditions (30 °C, 35 °C and 40 °C), along with cooling capacity [36]. It was also found that the reduction of the system pressure drop and the irreversibilities (except for the gas cooler). In the context of electric buses, a coaxial tube IHX system has demonstrated cooling capacities of 31.4 kW and COP of 2.88 at 35 °C, while also achieving heating capacities of 15.3 kW and COP of 1.78 at – 20 °C [37, 38]. Furthermore, designs that combine the IHX with an accumulator (ACCU/IHX) can simplify the overall system architecture while improving heat exchanger transfer efficiency [14, 39], as well as reducing the compression ratio in transcritical operation by lowering the optimal refrigerant charge [40].

Despite these benefits, IHX introduces operational challenges, mainly a significant increase in compressor discharge temperature. Discharge temperatures can reach 130 °C to 150 °C, which may exceed component design limits. To address this, researchers have proposed a two-stage compression system with an intermediate cooling compressor (ICC) [41]. IHX-equipped systems may also see long-term performance degradation, with up to a 15% COP reduction after ten years [42]. This loss can be partially recovered – by up to 25.48% – through control strategy adjustments that optimize discharge pressure.

The heat transfer process within the IHX causes a pressure drop on the low-pressure (suction) side of the circuit. This pressure drop increases the pressure ratio the compressor must overcome. As a result, the required compressor work rises. Optimal IHX design must therefore balance heat transfer effectiveness with the penalty of suction pressure drop. Only then can the system achieve a net positive effect on overall COP [33].

2.2 Performance enhancement via vapor injection and multi-stage compression

The performance of R744 ACHP systems can be improved by vapor injection, especially in EVs [32]. In a VI cycle, some refrigerant is injected into the compressor at intermediate pressure (Fig. 2a shows this process), reducing power consumption since only part is compressed from intermediate to high pressure, which increases the COP. In cold ambient regions, the application of a VI in an EV heat pump can increase its heating capacity [43], although the authors reported that the system needs regeneration components, such as an IHX and an expansion valve. These results were reinforced by further experimental research that indicates that a VI system can increase heating capacity by 75.7% and COP by 45.5% at an ambient temperature of −30 °C compared to a basic single-stage system [44, 45]. Yang et al. [44] further demonstrated that the performance of a VI-based R744 heat pump is significantly influenced by the electronic expansion valve (EEV) opening degree. Subsequent studies focused on the regulation characteristics of EEVs and their impact on system performance. Experimental testing of a VI-based transcritical R744 heat pump was conducted to develop an optimal COP regulation strategy for two EEVs. Results showed that adjusting the EEV openings can optimize COP and improve cooling capacity by up to 5.75% with an appropriate injection ratio [45]. However, integrating VI techniques wit R744 requires further investigation into advance components and controls, as highlighted in a comprehensive review by Mohaideen et al. [32].

The performance of the R744 HP can be also be enhanced by multistage compression with intercooling significantly over the basic single stage cycle [34]. A Two-stage compression with intercooling divides the compression process into two stages, separated by an intercooler (see Fig. 3) [46]. This configuration reduces the required work and lowers the final discharge temperature. High discharge temperatures are particularly problematic in R744 systems when there is a significant temperature difference between the heat sink and the heat source [8].

Experimental results show a 19.8% increase in the maximum cooling capacity, and 12.8% increase in the maximum COP at high ambient temperatures. The effects of the EEV and the compressor frequency were also studied, with the frequency having a higher impact [46]. In a subsequent study, the authors evaluated performance under cold conditions, achieving 50–132% increases in heating capacity and 18.9–61.9% improvements in COP at ambient temperatures between 0 and − 20 °C compared to a basic single-stage cycle. They concluded that the HP with ICC is also suitable in cold regions [41].

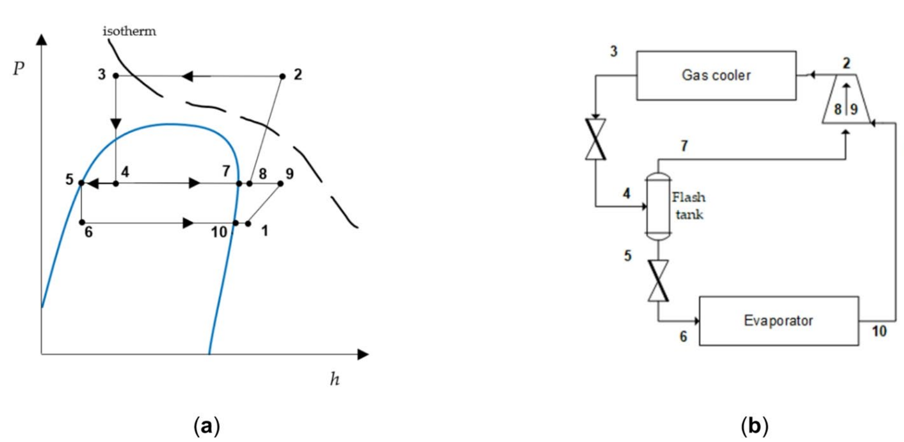

Fig. 2 Example of vapor injection-based cycle in a heat pump for EV. **a** *P-h* diagram; **b** schematics of the cycle

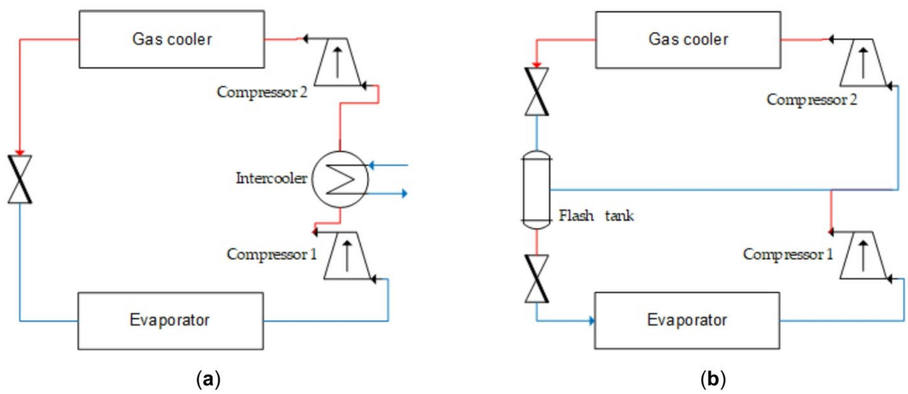

Fig. 3 Schematics of R744 two-stage compression systems using different intercooling techniques: **a** intercooler; **b** flash vapor injection

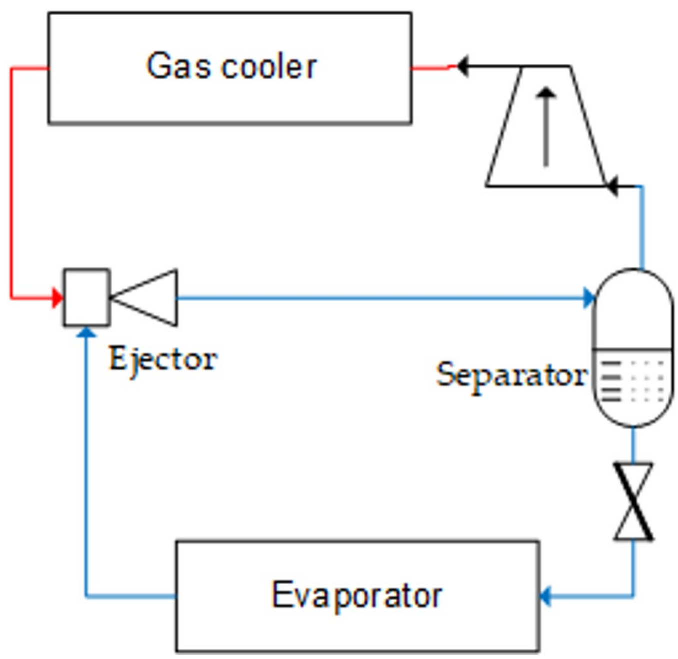

Fig. 4 Ejector expansion transcritical cycle

2.3 Performance enhancement via expansion valve irreversibility reduction

Technologies such as ejectors and expanders [47, 48] have been developed to reduce exergy destruction during throttling by recovering some expansion work. An ejector is a static device that uses the kinetic energy of high-pressure refrigerant to entrain and compress low-pressure vapor from the evaporator, with the mixed flow exiting at a pressure above that of the evaporator, as depicted in Fig. 4 [49]. This reduces the compressor's required pressure ratio and power consumption. Ejectors are well-suited for transcritical R744 cycles due to the large pressure difference between the gas cooler and evaporator [26].

Since the ejector is limited by operation conditions, a dual-ejector was proposed for heating and cooling modes and compared with a single-ejector system. It was found that the dual-ejector in parallel can increase the cooling COP by 17.3% to 23.4% compared to conventional cycles, and the heating COP by 18% to 19.79% when the ejector was optimized [50]. However, this study tested the cooling performance up to an ambient temperature of 38 °C. In another study, the authors found that ejector systems can improve COP by up to 15.22% at an ambient temperature of 45 °C. They can also extend the vehicle driving range by 19.6 km, a 5.28% boost. The performance was tested and compare with a conventional EXV system at ambient temperatures between 25 °C and 45 °C, with no testing in heating mode [51]. Despite their mechanical simplicity and cost-effectiveness, ejector performance is highly sensitive to geometry and operating conditions. Therefore, careful design and precise variable geometry are necessary to maintain optimal performance under varying conditions. Yang et al. investigated an ejector-expansion system and compared it with a basic regenerative and VI systems in heating and cooling modes at ambient temperatures between – 30 °C and 50 °C [52]. They found that the ejector systems reached the maximum COP improvement at 45 °C (31%) compared to the other systems.

Replacing the throttling valve with an expander is a thermodynamically efficient method of expansion work recovery (EWR), since the expansion valve is a highly irreversible component within the transcritical cycle [53]. Expanding high-pressure R744 through the expander generates mechanical work that can partly offset compressor power, often by coupling the expander to the compressor shaft. According to Barta et al. [47] most of the R744-based HP systems use a reciprocating compressor, but other compressors like rotary and scroll have been developed for transcritical cycles in EVs.

A novel scroll compressor-expander was proposed using a detailed mechanical-dynamic model, yielding a 9.8% COP improvement at a high discharge pressure of 15 MPa compared to a conventional system [54]. However, this study was not validated experimentally. A reciprocating compressor-expander was also simulated and compared with an R-407 C and a conventional HP system for an EV-bus application [55]. Under certain conditions in cooling mode, the EWR COP can be inferior to those of the other two systems. In heating mode, the maximum COP increase is 9.8% at 8 °C, and there is no further enhancement at temperatures below – 16 °C. System performance depends highly on expander design. An improper volume ratio between the expander and compressor can result in a COP lower than that of a basic R744 system. Expanders offer efficiency gains but add mechanical complexity, higher costs, and reliability challenges, especially when managing two-phase flow at the expander outlet. Limited expander efficiency and high liquid refrigerant cost have slowed adoption in commercial automotive applications.

2.4 Performance enhancement via improved heat exchanger layouts

In addition to modifications of the thermodynamic cycle, rearranging the configuration of heat exchangers provides an alternative approach to enhancing system performance. Conventional heat pumps typically use a single heat exchanger, also known as a gas cooler, to heat cabin air. Wang et al. [28] introduced a series gas cooler (SGC) configuration that incorporates two gas coolers in series for EV heating. The indoor gas cooler (IGC) supplies cabin heating, while the outdoor heat exchanger further cools the refrigerant before expansion. This arrangement increased heating capacity by up to 33% and COP by up to 32% compared to systems with a single gas cooler, achieving a heating capacity of 5.6 kW and a COP of 1.8 at -20 °C [28]. Numerical and experimental investigations of the SGC heat pump system confirmed these results, with average increases in heating capacity and COP of 33.7% and 35.0%, respectively, over conventional R744 systems [56].

A separate study demonstrated that employing a dual-source mode, utilizing both air and waste heat, in a R744 heat pump at -20 °C increased heating capacity by 6.4% to 19.2% and COP by 4.5% to 5.7% compared to the standard air-source heat pump (ASHP), thereby improving the EV's driving range by 9.4% to 15.6% [57]. During cooling operation, the indoor heat exchanger dedicated to heating, known as the heater core, remains inactive. The dual-evaporator concept repurposes this component as a second evaporator, as illustrated in Fig. 5, operating either in parallel or in series with the primary evaporator. This approach increases the total heat transfer area on the low-pressure side of the system without requiring additional hardware. The expanded evaporator area enables operation at a higher evaporation temperature, which reduces compressor pressure lift and power consumption. This modification increased system COP by 6 to 12%, offering a significant efficiency improvement, particularly in hot climates where the cooling performance of R744 systems is most limited [58].

Further, this paper discusses the benefits of reconfiguring the heat transfer areas and flexible layouts (Sect. 6.3).

2.5 Summary of performance enhancement technologies for R744 ACHP systems

This section reviews technologies designed to improve the performance of R744-based systems. In EVs heat pumps must operate reversibly to provide cooling during summer and heating during winter, which introduces a trade-off in technology selection. The development of these technologies reflects a strategic divergence in methods for enhancing the energy efficiency of R744 systems. Table 3 presents a summary of the principal technologies. The most effective solution should address the primary limitation of the R744 cycle in cooling mode, specifically the large throttling losses, while also capitalizing on its strength in heating mode at low ambient temperatures. EWR technologies, with a particular emphasis on ejectors, offer a promising approach. Ejectors directly target the main thermodynamic inefficiency of the transcritical R744 cycle, which is the considerable energy loss during throttling that reduces cooling performance in high-temperature environments. By recovering energy from high-pressure expansion to assist in

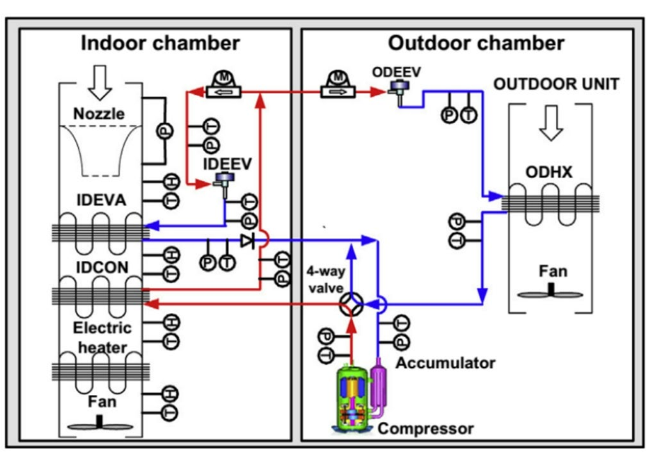

Fig. 5 Schematics of a dual evaporator R744 heat pump system for an EV [59]

Table 3 Summary of performance enhancement technologies for transcritical R744 vapor compression cycles

Technology	Operating principle	Reported COP/capacity improvement	Key advantages	Key challenges / complexity
IHX	Transfers heat from high-pressure R744 post-gas cooler to low-pressure R744 post-evaporator.	COP improvement: 7% to 25% [33, 36, 39, 40]	Simple, passive component; improves cycle efficiency and protects compressor	Adds cost and weight; Adds pressure drop to the suction line, rise discharge temperature.
VI	Injects a portion of R744 vapor at an intermediate pressure into the compressor.	Heating/cooling COP improvement: 45.5/9.5% Heating/cooling capacity improvement: 45.5/16.8% (at -30 °C/<40 °C) [32, 44, 45, 60]	Significantly boosts heating capacity and COP at very low ambient temperatures.	Increases system complexity (i.e., extra components needed); requires sophisticated control
Multi-stage compression	Compress the refrigerant into two or more stages by intercooling between stages.	Heating/cooling capacity improvement: 50–132%/19.8% Heating/cooling COP improvement: 18.9–61.9%/12.8% [41, 46]	Reduces total compression work, lowers discharge temperature, and improves compressor efficiency.	Increases system complexity, cost, and component number.
Ejector	Recovers part of available expansion work to lift compressor suction pressure, reducing compressor work	Heating/cooling COP improvement: 18–20%/>20% [48, 50–52]	No moving parts, robust, potential for low cost	Performance is sensitive to operating conditions; requires careful design and precise control
EWR	Recovers part of available expansion work to generate work (and thus electricity).	Highest theoretical efficiency potential [54–58]	Directly reduces electrical power consumption	Mechanically complex, high cost, and reliability concerns, especially with two-phase flow.

compressing refrigerant vapor from the evaporator, ejectors decrease the workload of the compressor and increase the cooling COP.

3 Thermal management systems architectures in EVs

Thermal management in modern electric vehicles does more than ensure occupant comfort. The performance, longevity, and safety of powertrain components rely on maintaining strict temperature ranges. The lithium-ion battery pack is especially sensitive. It requires cooling during fast charging and high-power discharge, and heating in cold conditions to prevent degradation and maintain efficiency [4]. The electric motor and power electronics, including inverters, also generate significant heat that must be dissipated [6]. The thermal management systems can be classified into cabin thermal management (CTM), motor thermal management (MTM), battery thermal management, and fuel cell thermal management (in the fuel cell EVs case). Previously, separate systems handled cabin HVAC, battery cooling, and powertrain thermal needs; however, this approach increased weight, complexity, and cost. To address these shortcomings and manage multiple thermal loads, integrated thermal management systems were developed. ITMS uses a single, centralized refrigeration circuit to coordinate all vehicle thermal loads and resources [29], maximizing overall energy efficiency and driving range.

Two features are unique for R744 transcritical systems: the existence of an optimal high pressure (OHP), which makes the control system challenging, and the use of the gas cooler. Different architectures have been investigated to improve the TMS, always under the restrictions imposed by the special characteristics of the transcritical R744 system.

3.1 Cabin comfort and thermal control

The primary function of the heat pump in EVs is to maintain cabin thermal comfort through heating or cooling. Traditionally, EVs have relied on PTC heaters for this purpose, but these reduce driving range. In addition to thermal comfort, the heat pump removes fog and frost from windows, thereby enhancing driving safety. Advanced control strategies are designed to reduce energy consumption and improve comfort, typically using the standard R744 heat pump configuration, which includes a compressor, gas cooler, EXV, evaporator, and sometimes an IHX. Recent studies have applied the Predicted Mean Vote (PMV)—a recognized comfort evaluation model [61, 62]—to achieve cabin thermal management objectives. For example, adjusting the thermal comfort target from PMV = 0 (neutral) to PMV = 0.5 (comfort boundary) enabled one control strategy to increase driving range by 7.3% and reduce annual operating costs by 6.9% at 35 °C [61]. Another approach, which used a weighted PMV model-based strategy, reduced compressor power by 9.1%, in summer and up to 18.8% in winter while maintaining comfort levels compared to traditional temperature-based control [62]. This approach involved a three-dimensional (3D) computational fluid dynamics (CFD) cabin model coupled with a one-dimensional (1D) heat pump model, thermal comfort estimation, and a PMV- proportional–integral–derivative (PID) strategy. Additionally, a data-driven model predictive control (MPC) method that simultaneously manages the compressor, expansion valve, and fan has been shown to decrease energy use by 13.33% to 20.27% over a six-hour period compared to a traditional proportional-integral (PI) controller, while maintaining passenger thermal comfort [63].

Current research reveals a tension between passenger comfort and energy conservation. Control strategies based on the PMV model show that energy savings are often achieved by operating at the comfort boundary rather than the neutral point. However, the control system plays a main role, while Zong et al. and Jiang et al. [61, 62] prioritize reducing compressor consumption, the data-driven MPC approach suggests simultaneous management of components to achieve energy reduction without sacrificing comfort. There is also a gap between 1D system simulations and 3D cabin environments, since 1D/3D coupling provides higher fidelity for PMV estimation, the computational cost of such real-time collaborative simulations limits their direct implementation in vehicle ECUs, pointing toward a need for reduced-order models in real-world feasibility. To mitigate high-temperature limitations, researchers have proposed increasingly complex configurations. For example, integrating a water gas cooler (WGC) between the IGC and the outdoor gas cooler (OGC), and optimizing the low-temperature radiator size, can increase cooling capacity by 4.9% relative to the baseline. This results in a COP of 1.55 at 43 °C, which improves comfort under high-temperature conditions [64]. Zhen et al. [65] investigated a similar configuration (IGC-WGC) integrated with an energy storage device (ESD) to achieve near-instantaneous cooling and stability. The use of the storage system decreased the cabin temperature by up to 3.67 °C during abrupt heat load changes and returned the system to a steady state 175 s faster than systems without storage. However, this introduces hurdles, such as the vehicle's volumetric constraints and the complexities of PCM. A study of an arrangement with two IGC-OGC [66] shows that the performance of these architectures is highly climate-dependent. R744 systems, in particular, are most sensitive to refrigerant microleakage. Even minor cumulative losses accelerate range degradation more than other refrigerants. Thus, the low emission advantage of R744 is maintained only if high-cost, leak-proof component manufacturing is achieved.

3.2 Heat pump system and battery thermal management

A key function of the reversible heat pump in the TMS is to maintain the battery pack within optimal temperature ranges, typically cited between 25 °C and 40 °C to preserve longevity and prevent thermal runaway. The ability to provide both heating and cooling facilitates effective thermal management throughout all seasons. During hot weather or rapid charging, the system directly cools the battery, whereas in cold conditions, it supplies heat to sustain the battery at its optimal operating temperature. This temperature regulation is essential for preserving battery performance, regenerative braking, and charging acceptance [67].

Direct refrigerant cooling of the battery represents a promising approach within ITMS.

However, a close look at recent studies shows that switching from conventional liquid-based cooling systems to direct refrigerant (two-phase) cooling creates new thermodynamic and control challenges. Direct refrigerant cooling, which circulates R744 through cold plates in direct contact with battery cells [68]., reduces thermal resistance and overall system weight by removing secondary fluid loops, while enabling faster and more uniform temperature control across the battery pack [11]. Yet, this setup is highly sensitive to vapor quality. Wang et al. [69] found that battery cooling performance relies strongly on evaporation temperature; for example, lowering it from 17.0 °C to 5.8 °C can boost the maximum COP by 8.38%, but greatly shrinks the stable operating window of the refrigerant.

This stability issue is further complicated by the cooling circuit layout. Studies comparing parallel and series setups show that while series arrangements can achieve a 13.5% higher COP at 35 °C ambient temperature, they risk high vapor quality at the outlet of the last battery modules, potentially leading to local hotspots. Fang et al. [70] reported positive effects on flow rate fluctuations in half-series arrangements, but further dynamic analysis is needed. This necessitates a precarious balance between maximizing latent heat of evaporation for efficiency and maintaining flow stability to prevent localized hotspots that could trigger thermal runaway.

At the system level, control strategies for direct-cooling BTM and CTM significantly impact vehicle performance. Implementing fixed return air temperature control can increase the EVs driving range by up to 10% compared to a fixed supply air temperature strategy [69]. Garrow et al. argue that the transcritical vapor compression system and the battery pack are highly non-linear, meaning that disturbances in battery heat generation can cause rapid pressure fluctuations in the R744 loop [71]. This calls for advanced multi-objective control strategies, which simultaneously satisfy several performance goals, to manage these non-linear constraints and maintain battery pack thermal uniformity. Furthermore, the architectural layout reveals a tension between steady-state efficiency and dynamic response. Song et al. [67, 72] suggest that although basic ITMS layouts can achieve a 10% COP improvement through optimized control, these gains are often diminished during the rapid heat-load fluctuations typical of fast charging. To improve dynamic response and efficiency, a PID control strategy has been proposed. A comparative study of four innovative configurations for EV cabin and BTM system indicates that a series-parallel configuration with an independent main heat exchanger provides the optimal balance between steady-state and dynamic performance [73].

Liquid-based battery cooling systems have received considerable attention due to their higher heat transfer coefficients compared to air-based cooling options [6, 74]. In this configuration, battery heat is dissipated via a coolant circulating through a secondary loop between the battery pack and a heat exchanger. Wang et al. [75] evaluated the performance and optimal control of an R744 HP with a chiller circuit for cabin and battery thermal management, using 50% ethylene glycol in heating mode. The system outperformed the conventional PTC heater, achieving an optimal COP of 2.277. Li et al. [76] incorporated a PCM storage as a link between the BTM and the heat pump to enhance winter performance. The HP layout followed a basic transcritical configuration, with ethylene glycol at 50% as the selected coolant. Ren et al. [51] proposed integrating an R744 HP with an ejector for cabin and battery TMS, reporting a higher COP than EXV system under all tested conditions; however, testing was limited to cooling mode at ambient temperatures of 25–45 °C. Recently, Jia et al. [66] simulated an R744-based CTM and BTM with PID control to investigate refrigerant leakage in both heating and cooling modes. The system layout included two outdoor heat exchanger (IHEX)/outdoor heat exchanger (OHEX), a coolant heat exchanger and a chiller for the battery coolant circuit, though details about the BTM system were not provided. Ji et al. [77] examined parallel-series and series-parallel arrangements between an IGC and evaporator, as well as radiator placement relative to the gas cooler. The parallel-series arrangement achieved a higher COP than the series-parallel, with the radiator front - connection performing better in heating mode and the back-connection in cooling mode. This study also addressed MTM and developed empirical models to estimate heat dissipation from battery and motor. Ren et al. [78] introduced an energy flow analysis approach for cabin, motor and BTM, quantifying the consumption of each TMS component under real test conditions using a time-scale refining methodology and interval suboptimal control to assess dynamic system performance.

The real-world feasibility of R744 BTM is constrained by a trade-off between energy density and thermal stability. This limitation creates a scalability paradox. Adding thermal buffers improves dynamic stability and waste heat recovery in cold climates. However, this also increases system weight and volume, which can offset the theoretical range gains from the R744 cycle's efficiency. Scientific consensus indicates that for R744 systems to be viable, development must go beyond bench-test performance. It must address the dynamic migration of refrigerant mass to ensure efficiency does not compromise the strict temperature gradients required for battery safety.

3.3 Waste heat recovery (WHR) from powertrain components

A holistic approach to EV thermal management conceptualizes the vehicle as an integrated thermal network. In BEVs, low-grade waste heat is generated by the battery pack, electric motor, and power electronics during operation [59, 74]. Rather than releasing this heat into the ambient environment, WHR strategies capture and repurpose it within the TMS. Figure 6 shows the conventional WHR strategy for a subcritical HP. For EV

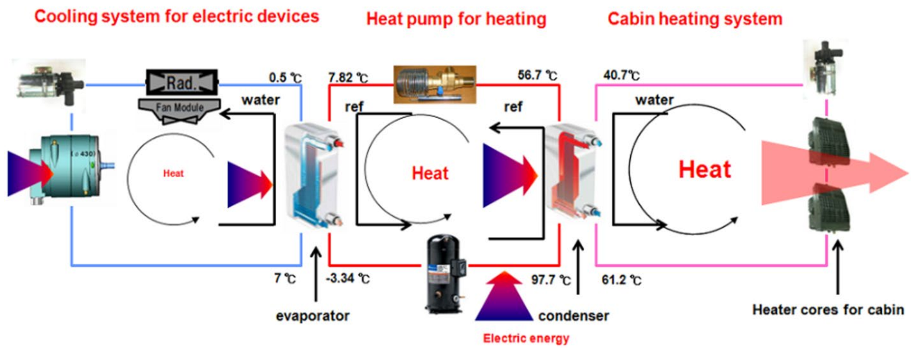

Fig. 6 Waste heat recovery strategy of a heat pump based on the use of low-grade waste heat from electric devices in EVs [80]

TMS using R744 the supplementary heat source operates similarly refrigerant-based systems, but the integration of high-pressure control increases system complexity. For example, a study on an R134 dual- source HP—which used both air and waste heat from electric devices [79]—added a water-refrigerant heat exchanger, improving efficiency at higher ambient temperatures. Similarly, in research on an R744 dual-source HP, the IGC and evaporator were connected in series, and additional valves were introduced, further complicating the system layout [57].

In heating mode, recovered waste heat serves as a higher-temperature heat source for the evaporator. By increasing evaporation temperature and pressure, WHR substantially reduces compressor workload and improves heating capacity and COP [81]. Typically, the system captures waste heat through a liquid-cooling loop and transfers it to the refrigerant in the outdoor heat exchanger, which acts as the evaporator during heating. Zhang et al. [82] evaluated operational modes in winter and implemented a three-stage control strategy to maintain cabin and motor temperatures within specified limits. Ethylene glycol functioned as the coolant, and the motor cooling circuit was linked to the refrigerant circuit via a plate heat exchanger. Their study examines the operational feasibility of transitioning between air-source and waste-heat modes in a real-world context. Optimization of this transition resulted in a battery State of Charge (SOC) improvement of up to 16.21% at – 20 °C. The ASHP-WHR mode also increased driving range in winter conditions. Zong et al. [83] introduced an improved parallel cooling configuration by adding a series cooling unit before the gas cooler and connecting it to the motor-radiator cooling loop. The system also included a chiller for the BTM system and a switching valve to enable transitions between heating and cooling modes. This arrangement resulted in a 14.8% increase in COP compared to conventional system, but the complexity of the enhanced parallel cooling architecture demands precise switching valve management to avoid pressure losses that could negate efficiency gains.

Similarly, the arrangement of heat exchangers presents a major system limitation. Kim et al. [81, 84] demonstrated that while placing a radiator in front of the outdoor heat exchanger can improve heating capacity and COP by up to 54.4% and 22.2% respectively, through air preheating, it results in a "conflicting result" for cooling performance. In cooling mode, this same arrangement results in a 40–60% reduction in cooling capacity due to increased air-side resistance and mutual thermal interference, posing a major challenge for year-round scalability. This is further explored through the lens of specific vehicle platforms and innovative materials.

He et al. [85] applied a thermal energy cascade utilization model to electric buses, demonstrating that incorporating motor WHR increases winter driving range by 19.14% to 20.90% compared to systems using only air. However, the transient availability of waste heat availability remains a limitation. To address this, Li et al. [75, 85] proposed using PCM to store recovered waste heat from the gas cooler, enabling preheating of the battery during parking and reducing the cold start energy demand.

Wang et al. [86] introduced a self-enhanced enthalpy system that, when combined with WHR, enables the transcritical R744 cycle to operate effectively below – 20 °C. This is achieved by using an IHX to regulate the gas cooler's outlet temperature. In dual-source mode, which uses both ambient air and recovered waste heat, an integrated R744 TMS boosts heating capacity by 12.68%, COP by 13.51%, and driving range by 9.1% compared to a standard ASHP [86]. This dual-source setup presents the highest theoretical potential. Teng et al. [57] report increases in heating capacity of 19.2% and COP of 13.5%.

This approach is vital for efficient thermal management in EVs operating in cold climates. An R744 heat pump system that recovers waste heat from the battery and motor increases heating capacity by 26.8%, COP by 27.3%, and driving range by 21.5% compared to a conventional ASHP system [72]. However, practical feasibility depends on whether a direct or indirect heating architecture is used. Direct integrated systems simplify the refrigerant loop and improve efficiency but pose risks of refrigerant leakage into the cabin and require more robust components to handle the high pressures of R744 [86]. While WHR is crucial for EV viability in cold-climate, future development must balance these peak performance gains with the increased manufacturing complexity and the reported penalties in cooling-mode identified in the literature.

3.4 System-level performance of integrated R744-based layouts

Integrating multiple heat sources, such as ambient air and waste heat, with diverse thermal loads −including the cabin, battery, and motor− results in a complex and interconnected system. The configuration and interconnection of heat exchangers, such as arranging cabin and battery chillers in series or parallel, significantly affect refrigerant flow distribution, pressure drops, and overall system performance [77]. Simulation and experimental studies indicate that incorporating motor WHR can improve the winter driving range of an electric bus by 19% to 21% compared with systems that rely solely on ambient air as a heat source [85]. This approach utilizes a cascade concept, preheating the battery with an R744 HP. In a separate study, five operational modes were evaluated, including parallel and series preheating of the cabin and battery, as well as WHR in single- or dual- source configurations. The highest COP was observed in series mode (COP = 3.29) and in single- heat- source mode (COP = 4.69). Additionally, a control strategy was implemented in which achieving system targets required precise switching of the EXV [72]. When operating among three modes at low temperatures (below – 20 °C), depending on available waste heat, the system can meet TMS requirements while preventing evaporator frosting. The system employed two ethylene glycol loops, each connected to a separate heat exchanger [86]. Further illustrating the complexity of ITMS, Zheng et al. [65] combined cabin, motor and battery thermal management and incorporated an energy storage device (ESD) (a water tank) tested in cooling mode. Multiple PID controls were required to achieve system objectives, and mode switching depended on precise coordination between the electronic expansion and automatic shutdown valves.

The addition of the energy storage device enhanced system stability and reduced fluctuations. A comprehensive review of ITMS systems for several refrigerants is available, which provides an overview of the various arrangements and valve-switching configurations [6, 29].

3.5 Summary of TMS architectures in EVs

In summary, Sect. 4 outlines the transition from basic cabin HVAC systems to advanced ITMS in modern electric vehicles. These holistic architectures employ a single R744 heat pump as a central energy hub to coordinate the thermal loads of the cabin, battery pack, and powertrain components. Key strategies include coupling cabin conditioning with BTM, often using efficient direct-refrigerant cooling, and recovering waste heat from the motor and electronics to significantly enhance heating efficiency in cold climates. This integrated approach is essential for optimizing overall vehicle energy efficiency and maximizing driving range. Different R744-based TMS architectures are summarized in Table 4.

4 Key operational challenges and optimization strategies

Advanced R744 ITMS in electric vehicles face multiple operational challenges. High efficiency and performance require precise thermodynamic regulation, effective refrigerant management, and careful consideration of environmental factors, all enabled by robust control systems. As a result, researchers have explored advanced optimization and control strategies to improve system performance in real-world applications.

4.1 Optimal high-pressure control

A defining characteristic of the transcritical R744 cycle is the significant influence high-side pressure on system efficiency. In subcritical cycles, condensing pressure is primarily determined by ambient temperature. In contrast, the COP in a transcritical cycle reaches its maximum at a specific optimal discharge pressure for each set of operating conditions [31, 87, 88]. Operating the system at non-optimal pressure can result in substantial performance losses [89].

While it is established that COP reaches a peak at a specific optimal discharge pressure, the practical realization of this optimum in EVs involves complex thermodynamic trade-offs.

Wang et al. [90] demonstrated that physical design constraints and the resulting temperature glide stablish a "pseudo-optimal discharge pressure" in EV heat pumps, which differs from the optimal pressure observed in conventional systems. The distinction matters because operating at pressures derived from standard models may lead to performance losses in mobile applications. In these settings, heat exchanger sizing and air-side conditions change rapidly. Additionally, long-term equipment aging presents an additional challenge. Yang et al. [42] reported that heat exchanger degradation increases the optimal discharge pressure over the vehicle's lifespan, which can cause COP losses of up to 15% if not addressed. These findings indicate that fixed predictive formulas, though computationally effective, are insufficient to maintain peak efficiency throughout the vehicle's lifecycle. Correction factors are needed to account for declining heat transfer efficiency. To address this evolving parameter, predictive formulas have been developed. For instance, Jiang et al. [61] found that multi-parameter formulas that include both gas

Table 4 Summary of R744-based TMS architectures in EVs

Reference	Model developed	Topic	Layout	BTM/WHR technique	Research focus
Ren et al. [51]	HP + cabin + ejector + battery	TMS (CTM + BTM)	Ejector	Secondary loop - coolant	Performance in cooling mode
Teng et al. [57]	Not reported (experimental)	WHR	IGC/evaporator series	Secondary loop - coolant	Three operation modes with dual source HP in heating mode
Jiang et al. [61]	HP + cabin + PMV	CTM	Two IHEX in series		Thermal comfort and cooling performance
Zong et al. [62]	1D HP + Cabin 3D + PMV	CTM	Basic		Thermal comfort and PID control with PMV target
Wang et al. [63]	HP + cabin	CTM	Basic		Thermal comfort and novel MPC in cooling mode
Wang et al. [64]	HP	BTM + MTM	IGC + WGC	Secondary loop - coolant	Performance in cooling mode
Zheng et al. [65]	HP + cabin + motor + battery	TMS + WHR	IGC + water gas cooler/chiller	Secondary loop - coolant	PID control and ESD performance in heating/cooling modes
Jia et al. [66]	Cabin	TMS (CTM + BTM)	Outdoor heat exchangers + IHEX + coolant heat exchanger	Secondary loop - coolant	PID control + refrigerant leakage in heating/cooling modes
Song et al. [67]	HP +cabin + battery + motor	TMS (CTM + BTM + MTM) + WHR	Basic	Two-phase direct refrigerant	Exergy analysis. Optimized control and multiple operation modes cooling performance

Table 4 (continued)

Reference	Model developed	Topic	Layout	BTM/WHR technique	Research focus
Yin et al. [68]	HP	BTM	Two IHEX in series	Two-phase direct refrigerant	Series and parallel configuration in cooling mode
Wang et al. [69]	HP + cabin + battery	CTM + BTM	Two evaporators	Direct refrigerant cooling	Control strategies in cooling mode
Fang et al. [70]	HP + battery	BTM	Two evaporators	Two-phase direct refrigerant	Parallel and half-series evaporator configuration performance in cooling mode
Song et al. [72]	HP +cabin + battery + motor	TMS (CTM + BTM + MTM) + WHR	Basic	Two-phase direct refrigerant	Parallel/series battery configuration. Single/dual source WHR in heating mode
Wang et al. [73]	cabin + battery	CTM + BTM	Basic + auxiliar heat exchanger	Direct refrigerant cooling	Four configurations of heat exchangers and PID control in cooling mode
Wang et al. [75]	Cabin volume	CTM + BTM	Basic	Secondary loop - coolant	Optimal control and performance in heating mode
Li et al. [76]	HP + battery + PCM	BTM + WHR	PCM storage	PCM	Performance in heating mode
Ji et al. [77]	HP + battery/motor (empirical)	TMS + WHR	Parallel/series IGC/evaporator	Secondary loop - coolant	IGC/evaporator and front/back radiator/gas cooler arrangement in heating/cooling modes
Ren et al. [78]	cabin + battery + motor	CTM + BTM + MTM	Basic	Secondary loop - coolant	Energy flow analysis

Table 4 (continued)

Reference	Model developed	Topic	Layout	BTM/WHR technique	Research focus
Kim et al. [81]	Not reported (experimental)	WHR	Basic	Stack coolant	Fuel cell + Heating mode performance, with and without heating core
Zhang et al. [82]	HP + cabin + battery	WHR	Plate heat exchanger	Secondary loop - coolant	Four function modes and three-stage heating control strategy
Zong et al. [83]	Not reported (experimental)	TMS (CTM + BTM + MTM)	Series gas cooler	Secondary loop - coolant	Enhanced parallel cooling system performance and optimized control
Kim et al. [84]	Not reported (experimental)	Fuel cell + HP	Basic	Stack coolant	Fuel cell + Gas cooler arrangement in cooling mode
He et al. [85]	HP + cabin + battery + motor	TMS + WHR	Basic + WGC	Secondary loop - coolant	PID control performance in heating mode
Wang et al. [86]	HP + cabin	CTM + BTM + WHR	Basic	Secondary loop - coolant	Three operation modes self-enhanced HP performance in heating mode

cooler outlet and evaporation temperatures provide greater accuracy than single-parameter models. Advanced architectures, such as the secondary throttling systems proposed by Wang et al. [91] offer significant thermodynamic benefits, including an 8.1% reduction in compressor power and a 9.4% increase in COP. However, these systems bring new control challenges, requiring unique fitting correlations for their specific optimal pressures.

Teng et al. [92]. attempted to simplify this by observing that the ratio of optimal discharge pressure to evaporator outlet pressure remains a constant 1.31, enabling a streamlined dynamic control strategy. Despite these architectural improvements, Yang H. et al. [93] found that ambient temperature remains the dominant variable, accounting for over 45% of the pressure variation in both single and two-stage systems, highlighting a persistent vulnerability to extreme weather conditions.

To overcome the limitations of offline, data-reliant formulas, online optimization strategies offer alternatives to traditional predictive formulas. The Fibonacci search method, for example, determines optimal pressure in real-time without relying on pre-measured data. While Glos and Solc [94] emphasize that such methods eliminate the need for pre-measured data, they can suffer from slow convergence amid rapid transient states. To address this trade-off, Ji et al. [95] introduced a hybrid strategy that uses an offline feedforward-feedback component for rapid estimation, followed by an online component for correctness. This combined method reduced cabin temperature settling time by up to 807 s compared to purely online methods, demonstrating that integrating rapid response and high-precision adjustment is essential for real-world EV feasibility. Furthermore, Ko et al. [96] quantified the potential of such active management, showing it can reduce compressor power consumption by up to 62% compared to conventional superheating-focused control, underscoring the high stakes of effective pressure management in extending EV driving range.

4.2 Optimal R744 charge management

Transcritical R744 systems are more sensitive to refrigerant charge levels than conventional HFCs [97]. Deviations from the proper charge, whether above or below recommended levels, quickly reduces the system COP and capacity. Experimental studies define an optimal charge plateau, a specific range that allows maximum performance [98, 99].

Effective refrigerant charge management is essential for optimizing the performance and efficiency of transcritical R744 heat pump systems, especially in automotive applications. Research has established optimal charge levels or ranges that maximize system performance. Experimental studies have determined suitable charge of 450 to 550 g in heating mode and of 500 to 550 g in cooling mode, depending on the expansion valve opening [39, 100]. Another investigation identified an optimal charge plateau between 500 g and 580 g at a compressor speed of 3000 $r \cdot min^{-1}$, and noted that the optimal charge amount decreases as compressor speed increases [101]. For larger systems, such as those used in electric buses, a normalized refrigerant charge (NRC) range of 0.248–0.336 is recommended to achieve maximum COP [102]. Additionally, a separate study reported an optimal plateau between 5 and 8 kg for electric bus systems [103]. The existence of this plateau demonstrates a range within which the system can sustain peak efficiency, providing some tolerance in charging.

R744 heat pump performance is highly sensitive to deviations from the optimal refrigerant charge, as seen in Fig. 7 for cooling mode. Insufficient refrigerant charge causes discharge pressure to exceed optimal values, resulting in rapid declines in COP and capacity. For instance, undercharged systems may experience COP and capacity reductions to 1.4 and 14.5 kilowatts, respectively, compared to maximum values of 1.7 and 25 kilowatts at optimal charge. Research indicates that performance losses are more pronounced undercharge than with slight overcharge [100, 102]. Insufficient charge can seriously increase irreversibilities within the heat exchangers, directly compromising system efficiency. These interdependencies underscore the necessity of precise charge control to maintain thermodynamic benefits. To mitigate performance degradation caused by issues such as refrigerant leakage, a novel control method employing a dynamic correction factor has been shown to recover up to 70.1% of the COP decline over time [104].

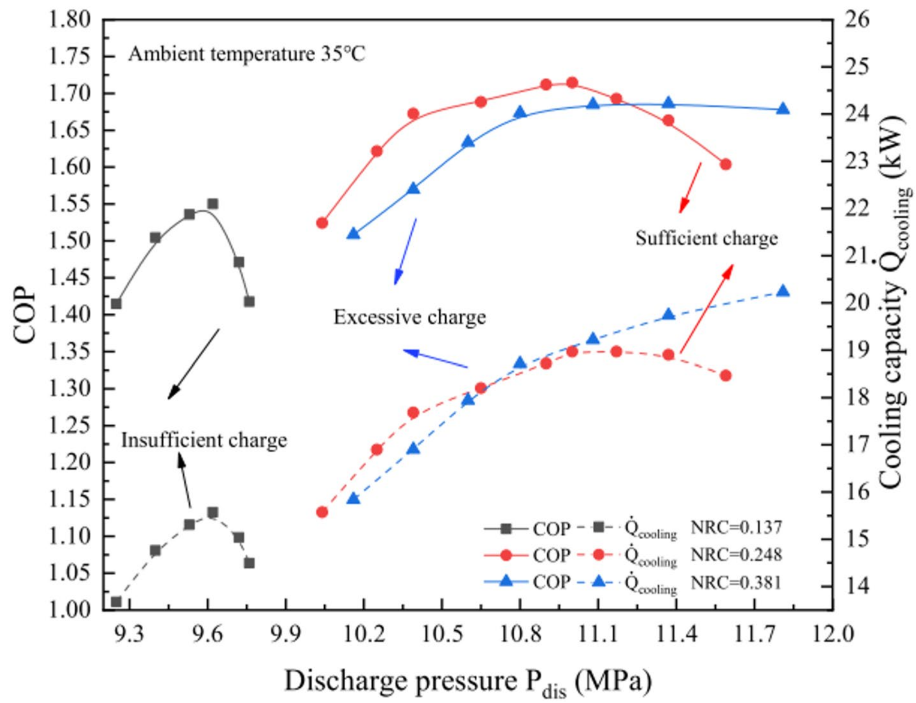

Fig. 7 Performance of a R744 system for EVs in cooling mode with respect of the high pressure under different refrigerant charge amount expressed as NRC [102]

In addition, other researchers developed a validated simulation model of an EVs R744-based TMS to quantitatively assess the impact of varying refrigerant microleakage rates on driving range, utilizing meteorological data from 34 cities in China. The study found that driving range degradation is more pronounced in warmer, cooling-dominant regions and recommends a maximum component-level leakage rate of 1.5 to ensure a maintenance interval of at least four years [66]. The relationship between refrigerant charge and other critical operating parameters, such as discharge pressure, is also significant. Ji et al. [105] examinated the linear relationship between optimal discharge pressure and refrigerant charge, proposing a corrected correlation that substantially reduces prediction errors compared to models that do not account for charge variations. These findings indicate that system control strategies, particularly for discharge pressure, must consider the current refrigerant charge to maintain optimal performance.

Dynamic operating conditions significantly affect the optimal refrigerant charge. Compressor speed and ambient temperature are especially influential variables. Jiang et al. [101] demonstrated that optimal refrigerant charge decreases with increasing compressor speed, indicating a direct relationship between the two parameters. In contrast, Song et al. [103] found that ambient temperature has a minimal effect on the charge range for bus systems but does influence refrigerant distribution within system components. The distinction shows that different variables affect both the quantity and distribution of refrigerants, highlighting the need for adaptive management strategies to handle real-world operational changes.

To address the complexities of refrigerant charge control resulting from dynamic conditions and system sensitivity, advanced monitoring and control method are being developed. Shao et al. [106] introduced a transcritical virtual refrigerant charge (TC-VRC) model that combines data-driven machine learning (ML) with grey-box techniques, such as multiple linear regression and support vector regression (SVR), to enable accurate online monitoring under dynamic conditions. Virtual sensors are particularly valuable in automotive applications, where installing physical sensors is often impractical. Recognizing the frequency of non-ideal charge operation, Jia et al. [107] developed a control method to regulate refrigerant distribution. This approach actively manages refrigerant within the system to mitigate the negative effects of inappropriate refrigerant charge, increasing the integrated part load value (IPLV) by nearly 37% when the charge deviated by 12% from the optimal range. These intelligent control and monitoring systems are expected to enhance the efficiency and reliability of R744 heat pumps in EVs. However, real-world feasibility is complicated by variable operating conditions and compressor speeds, which shift the required optimal charge; for instance, higher compressor speeds can reduce the optimal charge, creating a dynamic control conflict that conventional fixed-parameter correlations fail to address. These limitations point to a systemic trade-off: achieving peak efficiency demands refined, real-time virtual sensing or adaptive control methods to lessen the impacts of inappropriate charging, which otherwise compromises both the vehicle's driving range and the long-term reliability of the thermal components.

4.3 Frosting and defrosting dynamics

Frost formation on outdoor heat exchangers is a significant challenge for ASHPs in electric vehicles, particularly in high-humidity environments. Low temperatures and high compressor speeds accelerate ice accumulation, which insulates the coil and restricts airflow. When frost cover more than 40% of the surface heating capacity drops by 26–31%, and COP decreases by 22–30% [108]. Such efficiency losses directly compromise the vehicle's driving range, necessitating periodic defrost cycles. In reversible R744 systems, the standard approach is reverse-cycle defrosting (RCD), in which the system operates in cooling mode to send hot refrigerant through the outdoor coil [109]. However, this process is inherently parasitic, consuming excess energy and interrupting cabin heating, which creates a fundamental conflict between system maintenance and passenger comfort [110].Current research focuses on two primary objectives. The first is to develop intelligent defrost initiation criteria, ensuring defrost cycles occur only when necessary and thus reducing energy consumption and minimizing interruptions to heating [111].

Steiner and Rieberer [112] found that an ideal defrost cycle should be initiated when the temperature difference between ambient air and refrigerant reaches 10–20 K to maximize the average COP. For termination, while the gas cooler outlet temperature is a reliable indicator, the system's effectiveness is heavily influenced by expansion valve control. A parametric analysis reveals that a too-low refrigerant mass flow significantly extends defrost time, indicating that an optimal throttle opening is required to balance defrost speed with energy efficiency Steiner [113]. Furthermore, experimental evidence from periodic frosting-defrosting cycles indicates that ambient temperature and relative humidity have non-linear effects on capacity degradation, necessitating control logic that adapts to shifting environmental parameters [114].

The second objective is to optimize the defrost process to maximize speed and energy efficiency, even though these two goals may sometimes be at odds and require a careful trade. Recent evaluations have shifted toward frost-free control strategies that modulate system parameters, such as evaporation temperature and discharge pressure, to prevent accumulation without requiring auxiliary hardware [111, 115]. Another approach involves adjusting operational parameters to maintain frost-free conditions, though effectiveness is mainly limited by the evaporator's pressure drop. Notably, frost-free control has been demonstrated at relative humidity up to 87% at an ambient temperature of 0 °C [116]. Moreover, the practical feasibility of these methods depends on trip duration. Frost-free control is most effective for journeys longer than 60 min, while constant heating capacity control may be more efficient for shorter trips, where the cumulative effect of a single defrost cycle is lower [115]. Finally, a comprehensive global performance improvement control (GPIC) method has been proposed, prioritizing driving range rather than simple set-point maintenance. In cold, humid regions, GPIC can increase EV range by up to 10% compared to conventional optimal discharge pressure control by proactively preventing frost [110].

When frost buildup cannot be avoided, efficient defrosting is crucial. An ideal defrost cycle can be initiated when the temperature difference between the ambient air and the refrigerant reaches 10–20 K, which maximizes the average COP [112]. For efficient defrosting, the gas cooler outlet temperature is a reliable indicator of the end of the cycle. Different strategies are recommended for high and low-humidity environments to save energy [117]. Furthermore, the improper implementation of defrosting control logic can lead to severe energy waste. In large-scale applications like electric buses, experimental research demonstrates that utilizing the metal thermal storage of heat exchangers stabilizes system performance during rapid fluctuations across multiple frosting-defrosting cycles [109]. Collectively, these studies indicate that addressing frosting challenges requires a balance between advanced control logic, targeted hardware solutions such as IHXs, and optimized heat exchanger configurations.

4.4 Advanced control systems

Advanced control methodologies are essential for transcritical R744 heat pump systems in EVs, given their complex, dynamic behavior, which challenges traditional control methods. Key tasks include continuous tracking of the optimal pressure setpoint, effective management of refrigerant distribution across multiple operational modes, and rapid adaptation to variable driving conditions and thermal loads. The industry has shifted focus from reactive approaches, such as PID control and locally adaptive methods like extremum seeking control (ESC), toward proactive and predictive strategies. This transition is particularly significant for the TMS, as its energy consumption directly and indirectly influences the vehicle's operational range.

Recent advancements highlight the adoption of advanced techniques such as MPC and machine learning. MPC employs a dynamic thermal system model to predict future states and determine optimal control actions, including adjustments to compressor speed and valve positions to minimize energy consumption while satisfying thermal constraints [118]. ML and Artificial Intelligence (AI) area increasingly utilized to develop accurate digital twin models for control and to create intelligent algorithms for tasks such as optimal refrigerant charge detection and fault diagnosis [106, 119]. As system integration and complexity increases, control systems must become more intelligent, adaptive, and predictive to fully realize performance potential.

4.4.1 Model predictive control

Wang H et al. [63] proposed a data-driven MPC for the thermal management system of an EV cabin in cooling mode. This controller simultaneously managed the compressor, electronic expansion valve, and indoor fan to maintain an optimal high pressure and ensure passenger comfort, thereby minimizing the total power consumption, as already mentioned in Sect. 4.1. An experimental study of a data-driven MPC for a transcritical R744 system in EVs was presented by Miao et al. [118]. Their work involved developing a control-oriented model to predict system behavior and designing the MPC to find optimal inputs that maximize the COP while satisfying cooling or heating capacity requirements. The experimental results confirmed that the MPC strategy accurately forecasts system states and determines the best control inputs, achieving the highest possible operating COP under both fixed and variable ambient conditions. An example of MPC application in an R744 heat pump system in which the OHP was controlled via EEV opening by a PI controller, while the MPC controller determined the target value using an objective function and the heat pump dynamic model, is shown in Fig. 8.

4.4.2 Artificial intelligence and machine learning

Unlike the structured, model-based optimization of MPC, a second major paradigm in advanced control leverages AI and ML. These methods utilize pattern recognition and learning capabilities: ML can estimate unmeasurable system states, artificial neural networks (ANNs) enable direct non-linear control, and data the entire vehicle ecosystem inform adaptive control strategies.

Jia et al. [107] introduced a novel control method for automotive R744 heat pumps to address performance issues from improper refrigerant charge levels. Their proposed control logic regulated refrigerant distribution and increased the system's IPLV by 36.8% when the refrigerant charge was reduced by 12.12%. The study also found that performance improvement depend directly on the degree of refrigerant charge deviation [107]. The authors also studied "control disorder" in EV R744 thermal management systems, which occurs when automatic controls lead to instability and performance

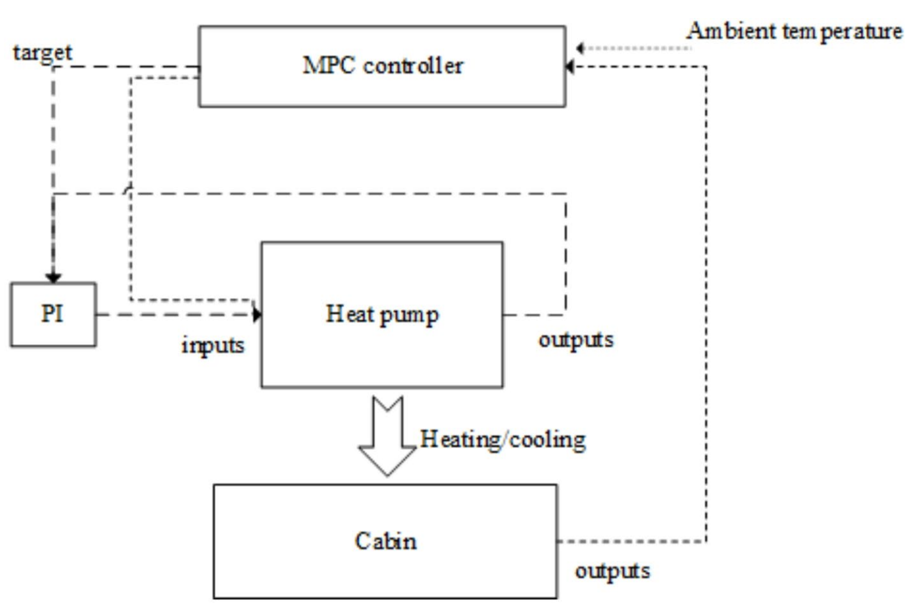

Fig. 8 Schematics of an MPC strategy for a transcritical R744 system

degradation− with a problem exacerbated by low indoor air flow, high ambient temperature, and low supply air temperature. To address this, they developed two Vehicle-to-Everything (V2X) suppression schemes using real-time external information to anticipate and prevent instability. Simulations showed these V2X-based methods prevented, on average, 70.1% of COP degradation, ensuring stable and safe operation [104].

Miao [119] reviewed intelligent control systems for EV-ACHP based on machine learning. They proposed a fuzzy inference system enhanced with machine learning models like fuzzy neural networks, enabling adaptive compressor control. This approach aims to overcome the linearity of traditional PID control and the reliance of standard fuzzy logic on fixed expert rules. By learning from data, the system can adjust interior temperature with high accuracy and low volatility. This capability enhances system adaptability and energy efficiency. Shao et al. [106] developed a TC-VRC detection model by integrating machine learning with grey-box modeling which outperforms conventional VRC models by predicting refrigerant charge levels with great accuracy in both heating ($R^2 = 0.933$) and cooling ($R^2 = 0.981$) modes. Real-time refrigerant charge monitoring is critical to for safe and efficient EV operation [106].

Teng et al. [120] developed an adaptive control strategy to enhance the cooling efficiency of an R744 indirect loop heat pump system under high-temperature conditions. The research demonstrated that, at maximum energy efficiency ratio (EER), the ratio of high pressure to gas cooler outlet temperature remains approximately 2.5. Implementation of the adaptive strategy resulted in a 7.5% increase in EER and a 13.1 °C reduction in discharge temperature at an ambient temperature of 40 °C [120]. In a subsequent study, the authors introduced a dual EEV sub-area control strategy to improve the heating performance of an R744 heat pump at low temperatures. At – 20 °C, this optimized approach increased average heating capacity by 11.6%, COP by 9.8%, and average outlet air temperature by 8.2 K. Real-world vehicle tests confirmed the system's effectiveness, demonstrating energy savings of 34.7% and driving range improvements up to 19.3% compared to an R134a-based system at – 20 °C [121].

Zhang et al. [82] introduced a three-stage heating control strategy for an R744 ASHP designed to enhance the winter driving range of EVs through WHR. The system transitions between standard ASHP mode, a dual-source mode combining ASHP and WHR, and a pure WHR mode, with switching logic determined by motor coolant temperature. Simulation and experimental validation demonstrated that this approach significantly increases battery SOC over a 7200-second cycle compared to a conventional ASHP. Optimization rates ranged from 8.07% at – 5 °C to 16.21% at – 20 °C. The strategy also extends driving range and maintains cabin thermal comfort [82]. Table 5 summarizes the two control approaches discussed.

Although advanced control strategies for ITMS are attracting research attention, current implementations still rely on conventional feedback methods, such as PID controllers, which regulate components, such as compressors, fans, and valves, individually based on temperature or load setpoints [10].The limited adoption of advanced approaches is mainly due to high computational demands, cost implications, and the lack of validation in real-world applications, as most studies remain confined to simulations or laboratory testing.

Table 5 Summary of advanced control approaches for transcritical R744 systems in EVs

Author	Methodology	Key control inputs	Primary optimization goal	Key reported outcome	Validation method
Wang et al. [63]	Data-driven MPC	Compressor speed, EEV opening, indoor fan speed	Minimize energy consumption while maintaining passenger comfort	20.27% energy reduction compared to PI controller in a 6-hour simulation.	Simulation
Zhang et al. [82]	Rule-based three-stage heating with WHR	Mode switching (ASHP, dual-source, WHR)	Optimize battery SOC and ensure cabin comfort in winter	16.21% SOC improvement over 7200s at – 20 °C vs. conventional ASHP.	Simulation
Teng et al. [92]	Adaptive control based on physical correlation	EXV opening	Maximize EER in high-temperature cooling	7.5% EER increase and 13.1 K discharge temperature reduction at 40 °C.	Experimental
Jia et al. [104]	V2X-based predictive suppression of control disorder	Compressor speed, EXV opening	Prevent convergence to low efficiency "pseudo-optimal" state	Prevented an average of 70.1% of COP degradation.	Simulation
Shao et al. [106]	Hybrid ML and grey-box virtual sensor for refrigerant charge	N/A (state estimation)	Accurately predict refrigerant charge level online	TC-VRC-III model achieved $R^2 > 0.98$ (cooling) and max RMSE of 1.36%.	Experimental
Jia et al. [107]	ANN-based state estimation and rule-based control	EXV opening, compressor speed	Maintain system performance under inappropriate refrigerant charge	36.8% IPLV increase when charge deviated by 12.12%.	Simulation
Miao et al. [118]	Data-driven MPC	Compressor speed, EEV opening	Maximize COP while meeting cooling/heating capacity target	MPC successfully converged to pre-calibrated optimal operating points.	Experimental
Miao [119]	Fuzzy neural network control	Compressor speed	Adaptively adjust cabin temperature with high accuracy	Review proposes ML-enhanced fuzzy logic for improved adaptability.	Theoretical review
Teng et al. [121]	Rule-based dual-EXV sub-area control strategy	EXV1, EXV2 opening	Improve low-temperature heating performance	11.6% heating capacity and 9.8% COP improvement at – 20 °C.	Experimental
Li et al. [122]	Adaptive fuzzy PI control	Compressor speed, EEV opening,	Optimize air cabin temperature, discharge pressure, and battery coolant temperature	Effective to stable and smooth control process	Simulation

4.5 Summary of key operational challenges and optimization strategies

This section identifies the main operational challenges of R744-based TMS in EVs. One key challenge is maintaining optimal discharge pressure under continuous regulation, which is essential for maximizing efficiency but varies with dynamic driving conditions. Additionally, these systems are sensitive to refrigerant charge; even small deviations from the optimal level can reduce performance, especially in integrated systems with variable operational modes. In cold climates, frost accumulates on the outdoor heat exchanger, reducing heating capacity and requiring energy-intensive defrost cycles. To address these issues, advanced approaches such as MPC and ML are being adopted to enable real-time optimization and intelligent system management.

5 Component-level innovations and constraints

The implementation of high-performance R744 TMS in EVs depends on both advanced cycle architecture and the development of components engineered for transcritical cycle conditions. The elevated pressures, temperatures, and distinct fluid properties of R744 require innovative design for compressors, heat exchangers, and other essential hardware.

5.1 High-pressure compressor technologies

Operating at high pressures often exceeding 100 bar requires compressors with exceptional mechanical robustness [25]. This high pressure and the high discharge temperatures inherent to R744 compression create a challenging environment for lubricants. Lubricant decomposition can lead to compromised performance and potential compressor failure. This has prompted research into oil-free compressor technologies [123]. Scroll compressors are promising for mobile R744 applications because of their compactness, low vibration, and continuous compression. However, a main challenge is managing internal leakage flows between adjacent compression pockets, which can significantly reduce volumetric and isentropic efficiency [123]. Ongoing research is optimizing scroll wrap geometry, using features such as asymmetric profiles with variable thickness. Such changes improve the built-in volume ratio and minimize leakage, enhancing compressor performance. According to Li et al. [124], a novel asymmetric scroll compressor design with variable wrap thickness, generated using trigonometric involutes, was effective for transcritical R744 heat pumps in EVs. This design improved the built-in volume ratio and operational stability by reducing the mass of the orbiting scroll. Key findings indicated that increasing radial clearance significantly lowered both isentropic and volumetric efficiencies by 40.82% and 28.91%, respectively, when widened from 30 μm to 200 μm. The compressor's exergy efficiency increased at higher suction temperatures and rotational speeds, reducing energy destruction during compression. C CFD studies also characterized the transcritical R744 process. The supercritical phase accounted for about 38.89% of a cycle, and pre-compression and over-compression phenomena affected overall efficiency. Other compressor types used in R744 heat pumps in EVs include rotary [83, 105, 125], radial piston [112, 113] and twin-screw [93].

5.2 Heat exchangers design

Designing heat exchangers for R744 systems involves complex optimization. In EV applications, these heat exchangers must be compact, lightweight, and capable of withstanding high pressures. Microchannel heat exchangers made from brazed aluminum are now standard in automotive systems. Their small-diameter flat tubes and louvered fins provides a high surface-area-to-volume ratio, which gives superior heat transfer in a compact form [126].

A main design challenge for the R744 gas cooler comes from the thermodynamic properties of supercritical R744. R744's specific heat capacity changes greatly with temperature, especially near the pseudo-critical point. This can cause a pinch point, where the temperature difference between the refrigerant and the air is minimized within the heat exchanger. The pinch may not occur at the inlet or outlet, which restricts heat transfer and reduces the effectiveness of the gas cooler. Design and modeling must address this pinch point for efficient heat rejection and optimal performance [127]. Simulation studies show that increasing depth and optimizing passes enhances heating capacity by balancing heat transfer and pressure drop [128]. Segment-by-segment modelling of microchannel gas coolers also shows that air temperature inhomogeneity at the outlet remains a challenge and can affect passenger comfort [128].

Operational parameters, such as air flow rate, are also critical to performance. The optimal rate is determined by experimentally identifying the points at which pressures and temperatures stabilize; beyond those points, further increases yield minimal gains. Wang et al. [129] found the optimal value for a single-row microchannel heat exchanger was about 2500 m^3/h. This rate is mostly unaffected by ambient temperature but rises slightly with compressor speed. Series configurations of indoor microchannel heat exchangers increase the heat transfer surface area, boosting heating capacity in cold climates. These systems outperform R134a models without supplementary electric heaters [14].

Despite recent advances, air temperature inhomogeneity at the gas cooler outlet remains important in component design [128]. Another overlooked challenge in early design studies is long-term performance degradation. Over a vehicle's lifespan, heat exchanger surfaces can foul or corrode, reducing heat transfer effectiveness. This degradation can change optimal system parameters, such as optimal discharge pressure, and cause efficiency to decline unless addressed in control strategies [42].

Beyond degradation issues, heat exchangers, compressors, and other components may be subject to thermal stress due to the high operating pressures in R744 systems. This can accelerate material wear and contribute to long-term reliability issues. The elevated pressure levels also require specialized welding and pressure-resistant joints, which demand skilled personnel for installation and maintenance. Proper sealing and meeting safety standards adds complexity. These technical demands increase system costs and may limit large-scale adoption.

5.3 Accumulators and expansion valves for high-pressure operation

The management of refrigerant charge and high-side pressure regulation constitutes a critical thermodynamic trade-off in transcritical R744 systems, where typical passive components are insufficient to maintain peak efficiency. Accumulators serve as the primary buffer for charge fluctuations and are key to managing refrigerant migration and protecting the compressor [98]. Placed on the suction line before the compressor, the accumulator stores excess liquid refrigerant, ensuring only vapor enters the compression chambers [40, 98]. Many modern systems integrate the accumulator with an IHX, combining charge management and performance enhancement into a single component [101, 105, 106, 130]. The accumulator's dynamic behavior, especially during start-up, shutdown, and mode transitions, is critical for stable and efficient system operation. However, this assimilation brings in complex dynamic behaviors; experimental visualizations using mirrored accumulators have shown that refrigerant migration during start-up and shutdown cycles markedly alters the available active charge [98]. Furthermore, the system must balance the accumulator's storage capacity with the need for stable oil return, as the oil circulation rate is inherently linked to the refrigerant mass flow and valve modulation [39].

The inadequacy of mechanical expansion valves in these systems stems from the extreme sensitivity of the transcritical cycle to discharge pressure. Consequently, EEVs are necessary for active mass flow modulation. The regulation of EEV opening directly impacts the system's internal state; while increasing the valve opening generally reduces discharge pressure and temperature, enhancing isentropic and volumetric efficiencies, this relationship is not linear [39]. Research into secondary throttling cycles demonstrates that dual-EEV configurations (EXV1 and EXV2) enable more precise control over intermediate pressures, successfully decoupling the regulation of the compression ratio from the evaporator's superheat requirements [121, 131] [Wang 2023.pdf [130], Teng 2025.pdf]. Such sub-area control strategies are vital for maintaining heating capacity in extreme low-temperature conditions, where the EEV's response time critically affects the system's ability to track the optimal pressure setpoint [121].

Precise high-side pressure control makes mechanical expansion valves inadequate for transcritical R744 systems. EEVs are essential as they actively modulate refrigerant mass flow. By adjusting EEV opening in response to sensor inputs (pressure, temperature), the control system regulates high-side pressure to track the optimal setpoint as operating conditions change [121, 131]. The EEV's regulation and response time critically affect the system's ability to maintain peak COP and capacity in moving vehicle [45].

Effective EEV regulation improves compressor efficiency and system performance. Increasing the EEV opening lowers the compressor discharge temperature and pressure, thereby enhancing isentropic, volumetric, and total efficiencies, as shown in experimental research [39]. Achieving maximum system COP requires identifying the optimal refrigerant charge for each EEV setting. The ideal charge level changes with valve position.

Determining the optimal refrigerant charge is challenging due to its dependence on valve position and ambient conditions. Although a charge level between 450 g and 550 g is frequently cited as a stable range for automotive heat pumps [100], the peak COP for a specific EEV setting varies as the valve opening changes [39]. Under-charging is especially detrimental; a 20% reduction from the recommended level can result in a COP decrease of more than 10% because of rapid heat transfer degradation in the gas cooler [105]. In contrast, excessive charge may cause charge plateau periods where additional refrigerant does not improve performance but increases discharge pressure. To address these sensitivities and mitigate refrigerant leakage risks, recent research has focused on virtual refrigerant charge sensors and data-driven MPC. These approaches employ machine learning to estimate charge states in real-time [106] and optimize system inputs based on predicted behavior within a finite time horizon [118]. By integrating these advanced controls with robust hardware capable of supporting multiple operational modes, such as cabin heating, battery cooling, and fast charging, the R744 system can overcome the inherent limitations associated with high-pressure operation [114, 130].

5.4 Summary of component-level innovations and constraints

This section reviews the components required for high pressure, high temperature R744 TMS. High-pressure compressors, especially scroll types, are paramount, though challenges such as internal leakage and lubricant stability require further research. Microchannel heat exchangers are standard in gas coolers and evaporators because they are compact and efficient but must be engineered to address pinch point challenges. The system uses supporting components, such as accumulators for refrigerant management and EEVs for precise pressure control.

6 Future directions and research outlook

Future research on R744-based TMS in EVs may focus on strategies to reduce total life-cycle costs. Key research directions include developing advanced materials that withstand high operating pressures while minimizing weight and material degradation. Simplified and reconfigurable system architectures can address integration challenges and improve adaptability across diverse vehicle platforms [74]. Progress in next-generation components and flexible configurations is anticipated to enhance thermal management efficiency. Integration with comprehensive vehicle TMS is essential for optimizing energy utilization and component interactions. The implementation of smart control systems and automated manufacturing processes is expected to improve system reliability and production efficiency. Additionally, comparative assessments of R744 against other emerging refrigerants, such as propane and low-GWP synthetic options, will be crucial to validate its long-term competitiveness and guide strategic refrigerant selection for future EV platforms.

6.1 Comparative insights: R744 versus traditional refrigerants, and emerging alternatives for EVs heat pumps

R134a currently remains the main refrigerant in EVs [11, 132]. Alternatives being studied include R152a, R1234yf, R290, and R744. R290, is a natural hydrocarbon refrigerant with zero ODP and low GWP [18, 133]. These features make R290 a viable alternative to R744, but its high flammability (safety level A3) remains a significant limitation. Unlike non-flammable R744, R290 requires strict safety measures, such as secondary loops or charge limits, to reduce explosion risks in automotive cabins. A successful transition must balance thermodynamic efficiency with regulatory and safety standards [21, 132, 134]. Yang et al. [135] compared R744, R290, and R134a in EV-TMS under different conditions and climate regions. Results show that, in cooling mode, R134a TMS achieves higher COP, greater thermal management energy consumption factors (TMEF), and a longer driving range than R744 and R290 systems. R290 TMS gives a slight advantage over R744-based TMS in cooling. In heating mode, R744-TMS is more efficient and maintains adequate heating capacity down to – 30 °C, whereas R134a and R290 systems require auxiliary PTC heaters at low temperatures. To further contextualize these findings, Table 6 summarizes key studies that assess the performance of R744 relative to other refrigerants in heat pump technologies for electric vehicles. The findings consistently highlight the advantages of R744, especially its superior heating performance in cold climates.

Experimental studies show that R744 systems deliver a heating capacity that is over 83% higher than that of R134a systems at – 10 °C. They also maintain a high COP at -20 °C [14]. These benefits means 34.7% energy savings and up to 16.6% more driving range compared to R134a systems with PTC heaters [121]. However, R744 has limited cooling performance due to significant thermodynamic losses. Exergy analysis shows that the expansion valve is the main source of inefficiency, accounting for over 36% exergy destruction. As a result, the R744 system exergy efficiency (SEE) is lower than that of 1234yf in cooling mode [136]. To overcome these issues, researchers are testing R744-based blends, like R744/R290 and R744/R41, which may improve COP for heating and cooling by optimizing thermodynamic properties and lowering operating pressures [137, 138].

When comparing R744 with R407C systems, R744 consistently provides sufficient heating in cold conditions without requiring auxiliary PTC heater; While R407C systems achieve up to 17% higher COP than R744 in cooling mode under most conditions [139]. Figure 9 presents COP values reported by various authors, as summarized in Table 6. In cooling conditions (35 °C ambient temperature), the R407c achieved the best COP reported [139], followed by R744, R134a, and R290; However, the performance was tested under different parameters, and different cooling capacities [139, 140]. As can be seen, R290 outperforms R744 under the same conditions [135]. In heating conditions, R744 always achieves the highest COP at the same ambient temperature and heating capacity.

6.2 Smart controls and systems

Effective EV thermal management relies on predictive, intelligent controls instead of reactive approaches. Integrated systems involve multiple, interacting thermal loads and changing conditions [125, 141], requiring control methods that anticipate future needs. MPC is essential, using dynamic models to forecasts system responses and compute optimal control actions that minimize energy use while maintaining temperature limits for the cabin, battery, and powertrain [118].

Efficient, accurate digital twin models running on the vehicle's control unit are needed for advanced controls [142]. AI and ML expand these capabilities. ML algorithms create precise data-driven models for MPC or develop adaptive controllers. These adapt to driver behavior and environmental conditions, personalizing and improving thermal performance [119, 143].

6.3 Next-generation components and novel system configurations

The progression of R744-based TMS will depend on innovations at both the component and system levels. Future research is expected to address the following areas:

6.3.1 Next-generation components

The commercialization of efficient, compact, and oil-free compressors for mobile R744 applications is essential. Integrating the compressor and expander into a single, cost-effective compression-expansion unit may facilitate widespread adoption of expansion work recovery [53]. Additive manufacturing enables the development of novel heat exchanger designs optimized for R744. Continued progress in materials and manufacturing is necessary. The use of lightweight, low-cost composite materials for heat exchangers and system piping can reduce vehicle weight and costs while maintaining the required strength for high- pressure operation. For compressors, improvements in coatings, sealing technologies, and lubricants are required to enhance efficiency, reliability, and operational lifespan [20].

6.3.2 Novel, flexible, and reconfigurable layouts

Future system architectures are expected to be increasingly adaptive and multi-modal. Intelligent valves will enable systems to dynamically alter refrigerant pathways and switch between operational cycles. For instance, a system may employ a simple single-stage cycle under mild conditions and transition to vapor injection during extreme cold, thereby maintaining optimal efficiency [144]. Flexible operation for both

Table 6 Comparison of R744 and other refrigerants for different configurations

Reference	Refrigerant	System	EV application	Operation mode/ Ambient temperature (°C)	Performance metrics	Key findings
[14]	R744 vs. R134a	HP + ACCU/IHX experimental bench	Passenger EV	Cooling: 40 °C; Heating: – 10 °C, – 20 °C, – 25 °C	Heating capacity (-10 °C, 6000 RPM): 7.38 kW (R744) vs. 3.99 kW (R134a). Heating capacity (– 20 °C): 7.5 kW, COP: 2.16 (R744). Cooling capacity (40 °C): 7.52 kW, COP: 1.36 (R744).	R744 provides 83% more heating capacity than R134a at 10 °C. Cooling performance is comparable.
[55]	R744 (basic and advanced) vs. R407C	HP simulation; Advanced R744 + EWR	Electric Bus	Cooling and heating across 5 Chinese climate zones.	Cooling COP improvement: Advanced R744 system is up to 13.59% better than R407C. Heating COP (16 °C): R744 COP is 32.88% higher than R407C.	R744 system with EWR outperforms R407C in cooling. The choice between R744 and R407C is climate-dependent, with R744 superior in colder zones.
[108]	R744 vs. R134a	HP focus on frosting experimental bench	Passenger EV	Heating: 0 °C	Heating capacity reduction (due to frost): ~30% for both systems. Frost coverage: R134a shows more severe frosting (72.04%) vs. R744 (55.53%).	Both systems suffer a similar ~ 30% heating capacity loss. Frosting significantly impacts R134a's suction pressure more than R744.
[116]	R744 vs. R134a	HP simulation. Focus on frost-free control.	Passenger EV	Heating: – 25 °C to 0 °C	Max humidity for frost-free operation (– 10 °C): 85% for R744.	R134a systems are harder to control for frost-free operation than R744.
[121]	R744 vs. R134a	Real Vehicle Test; Novel dual EXV control for R744.	Passenger EV	Heating: – 10 °C, – 15 °C, – 20 °C; Cooling: 40 °C	Energy savings (– 20 °C): R744 consumes 34.7% less energy than R134a + PTC. Range mprovement: +16.6% at – 10 °C, + 9.3% at – 20 °C for R744.	Dual-EXV control strategy for R744 improves heating capacity by 11.6% and COP by 9.8% at – 20 °C.
[135]	R744 and R290 vs. R134a	TMS simulation; in cooling/heating modes	Passenger EV	Cooling: 25 °C to 45 °C; Heating: -30 °C to 7 °C	Heating mode (up to – 30 °C): R744/R290/R134a COP = 3.12/2.23/2.46. Cooling mode: R744/R290/R134a COP = 2.36/2.84/3.14	In heating conditions, R744 TMS has the lowest TMEF and highest driving range, eliminating the need for PTC. In cooling, R744 TMS has the highest TMEF and lowest driving range.
[138]	R744/R290 blend vs. R744	Modified autocascade HP- model	Passenger EV	Heating: – 20 °C to 10 °C	Best COP (– 20 °C): 2.7 (80% R744)	The R744/R290 ACHP shows a 12.3% higher COP than a single-stage R744 system at – 20 °C
[136]	R1234yf, R152a, R744	HP + IHX simulation	Passenger EV	Various	Cooling exergy efficiency: R744 SEE is > 20% lower than R1234yf. Heating exergy efficiency: R744 SEE is ~2x higher than R1234yf.	R744 heating efficiency is confirmed from a second-law perspective.

Table 6 (continued)

Reference	Refrigerant	System	EV application	Operation mode/ Ambient temperature (°C)	Performance metrics	Key findings
[139]	R744 vs. R407C	HP simulation includes PTC for R407C.	Bus/Railway EV	Annual cycle simulation across 116 cities.	COP (heating < – 29 °C): R744 COP is > 120% R407C + PTC COP.	R744 shows better heating capacity, especially in severe cold.
[137]	R744/R41 blend vs. R744	HP simulation	Passenger EV	Cooling and Heating: – 20 °C to 30 °C	COP improvement: Up to 40.5% with 20% R41 at 20 °C.	R744/R41 blends significantly improve COP, but the benefit diminishes at extreme low temperatures due to reduced suction density
[140]	R744 vs. R134a	HP experimental bench. Series IGC for R744 vs. Parallel for R134a.	Passenger EV	Cooling: 15 °C to 45 °C; Heating: – 5 °C, – 10 °C, – 15 °C	Heating capacity (– 10 °C, 6000 RPM): 7.38 kW (R744) vs. 3.99 kW (R134a). COP (heating – 15 °C, same capacity): 3.53 (R744) vs. 1.80 (R134a).	R744 heating capacity is at least 50% larger than R134a. At the same heating capacity, R744's COP advantage grows at lower temperatures, reaching a 96% improvement at – 15 °C.

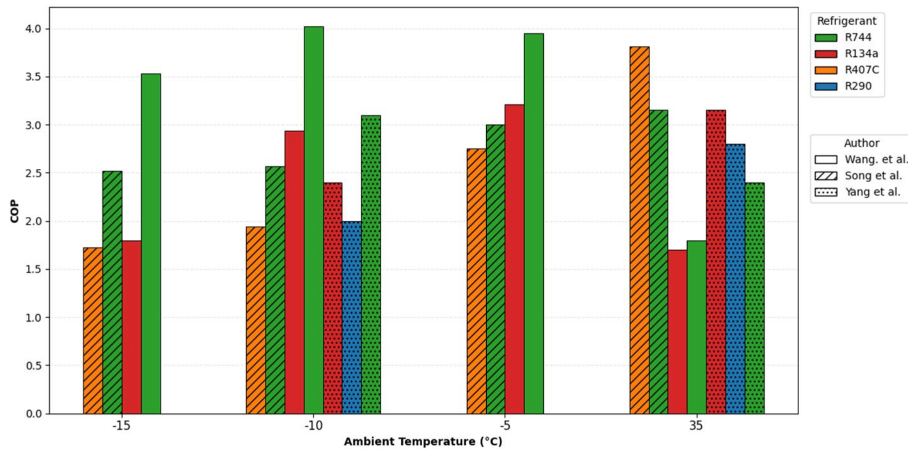

Fig. 9 Performance (COP) values for R744 and other refrigerants in EV heat pump applications, as reported by various studies summarized in Table 6

dehumidification and heating is feasible [145].Integrating technologies, such as operating an ejector with vapor injection or combining an evaporator with an ejector (Fig. 10) may maximize performance across a wide range of operating conditions.

The elevated operating pressures associated with R744 introduce significant safety and reliability challenges. Preventing component failures that could result in high-pressure refrigerant release requires robust design, comprehensive testing, and careful material selection. In direct-expansion systems, a primary safety concern is the potential for R744 leakage from the in-cabin heat exchanger. Although R744 is non-toxic at low concentrations, a rapid leak may decrease cabin oxygen levels and create an asphyxiation hazard. Consequently, secondary loop systems have been developed as an alternative [146]. In these systems, the R744 circuit is confined to the front-end or underbody, where it cools or heats a secondary fluid, typically water-glycol. This secondary fluid is then circulated to a heat exchanger within the cabin, thereby preventing high-pressure R744 from entering the passenger compartment. However, this approaches a performance trade-off. The additional heat transfer step increased pumping requirements consume more energy, resulting in lower efficiency compared to direct-expansion systems [147, 148].

In addition to secondary loops, to address the challenges of high operating pressure and reduced performance under specific conditions, researchers have proposed R744-based refrigerant mixtures such as R744/R41 and R744/R290 [137, 138]. The R744/R41 blend lowers operating pressure, while R744/R290, a zeotropic mixture, can be classified as A1 (non-toxic, non-flammable) with the appropriate mass fraction [132]. Despite these innovations, practical challenges persist. Specialized sensors are needed to detect leaks due to the compositional variability of zeotropic mixtures [20]. This also results in increased phase-separation complexity and introduces factors such as the influence of oil on system performance. Furthermore, heat exchanger design must consider the properties of the R744-propane mixture, alongside the added cost and weight of supplementary components [138]. Consequently, vehicle manufacturers must balance safety and efficiency based on operational requirements and risk assessments. Vehicle manufacturers must carefully evaluate this trade-off between safety and efficiency based on specific operational requirements and risk assessments.

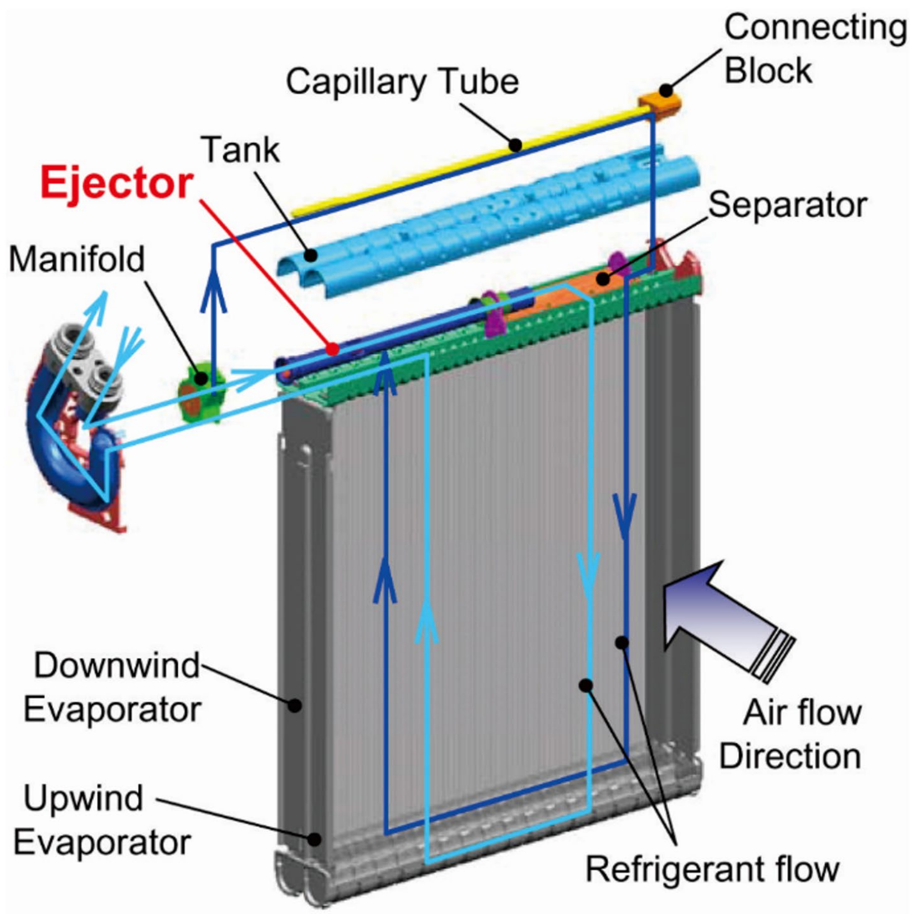

Fig. 10 Ejector-evaporator design [59]

6.4 Integration with vehicle management systems

A primary future direction for EV thermal management is its integration with the broader transportation and energy ecosystem [11]. V2X communication enables vehicles to access real-time environmental data, including traffic conditions, topography, and weather forecasts [104]. MPC systems can utilize this external data, allowing the ITMS to optimize decision-making. Advanced integration links the vehicle TMS with other onboard systems and external data sources to enhance energy efficiency. In fuel cell vehicles, the R744 AC system can assist in cooling the fuel cell stack, increasing heat dissipation by up to 36%. Additionally, waste heat from the stack can improve heat pump efficiency [149], potentially extending driving range by up to 37%. Managing this complexity necessitates advanced control strategies. By leveraging vehicle connectivity for weather and traffic data, an MPC system can achieve 10–14% greater energy savings than conventional controllers by predicting thermal loads and optimizing system operation [11]. The configuration of the heat exchangers is also critical; in cooling mode, R744 AC system can outperform traditional R134a systems [150].

Integrating the heat pump with the BTM system can result in substantial improvements in energy efficiency and performance. Waste heat generated by R744 heat pump can be stored in a PCM unit and subsequently used to preheat batteries during winter, thereby reducing energy consumption at low ambient temperatures [65, 76]. Direct refrigerant cooling from the heat pump system is also effective for managing thermal

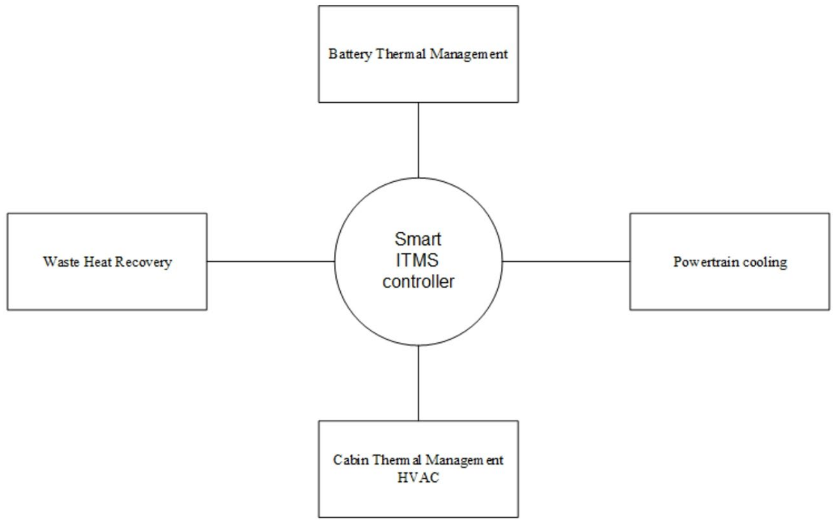

Fig. 11 ITMS structure for EVs

loads during extreme conditions, such as fast charging or significant environmental fluctuations [70].

A principal future direction for EV TMS involves transitioning from optimizing individual subsystems to developing a fully ITMS [29]. In this configuration, conventional distinctions between cabin HVAC, BTM, and powertrain cooling are dissolved. The ITMS functions as a unified thermal network, intelligently routing and managing energy to minimize battery consumption [6]. Figure 11 presents a schematic representation of this approach.

An ITMS would employ a multi-modal R744 heat pump as its core component, capable of addressing multiple thermal loads either simultaneously or sequentially. For instance, waste heat from the battery during fast charging could be redirected to heat the cabin, or the heat pump could cool the powertrain while simultaneously dehumidifying cabin air [151]. This strategy achieves efficiencies that are unattainable with separate systems. The objective is to treat all heat sources −the powertrain and ambient air−and all heat sinks—including the cabin, battery, and external air− as interconnected nodes within a single intelligent network, with the ITMS efficiently managing energy flows [29].

The long-term goal for this technology is to achieve a state of "thermal invisibility" where the TMS operates so efficiently that its energy use has minimal impact on the vehicle's primary transportation function. Achieving this will require advances in hardware and the development of advanced cyber-physical systems. These systems will integrate physical components managed by a predictive, AI-driven software. This intelligent system will use data from the vehicle, its occupants, and the environment to optimize energy management and maximize thermal efficiency.

6.5 Identified research gaps and unresolved questions

Despite substantial research, several key areas require further study to ensure robust, widespread deployment of R744 systems in EVs:

- Long-Term Performance and Reliability: Most studies focus on new systems under controlled conditions. Research on the long-term degradation of R744 systems over a typical 10–15-year vehicle lifespan is limited. Component wear, heat exchanger fouling, and lubricant migration can alter performance and lower efficiency. A thorough understanding and accurate prediction of these aging effects are vital for durable system design and adaptive control strategies [42].

- Dynamic Refrigerant Charge Management: Although the sensitivity of R744 systems to refrigerant charge is well established, identifying a cost-effective and reliable method for real-time monitoring and management of active refrigerant charge remains unresolved. Because dynamic refrigerant migration during transient operations can cause temporary performance degradation, the proposed solution is to implement a control system that actively monitors and adjusts refrigerant distribution in real time to maintain stability and efficiency.
- Cost-Effective Advanced Components: Promising technologies such as two-phase ejectors and expanders remain underused in the automotive industry due to cost and complexity. Research should focus on simpler designs and affordable manufacturing for these high-pressure components to enable efficient cycles.
- Standardized Performance Metrics for Integrated Systems: Evolving thermal management needs have driven the development of standardized test protocols and metrics that reflect system-wide energy savings. Since existing component- and subsystem-level metrics fail to capture integrated benefits, industrial consortia and standards bodies should urgently establish robust integrated performance metrics to enable meaningful comparisons of TMS architectures for engineers and consumers [29].
- Research on real-world applications: Current research on R744-based ITMS in electric vehicles, particularly regarding real-time, data-driven modeling under dynamic conditions. Few studies evaluate TMS performance outside controlled environments. Future research should focus on validating advanced technologies, components, and control strategies in actual vehicle settings. Key technical challenges include high operating pressures, safety standards, component weight, cooling efficiency in warm climates, lubricant stability, impacts on driving range, and control system reliability. Addressing these issues requires empirical studies that assess system performance beyond simulations and laboratory tests.

Adopting R744-based HPs in EVs brings technical and operational challenges. High operating pressures in warm climates raise discharge temperatures and stress compressors, driving the development of innovative components or enhanced strategies such as vapor injection. Environmental factors, like solar radiation and extreme ambient temperatures, reduce efficiency and threaten component durability. While research often focuses on heating improvements to mitigate range loss in cold climates, the transcritical R744 cycle delivers effective heating at low temperatures but requires further analysis for cooling at higher temperatures. Lubricant selection is also crucial because refrigerant-lubricant interactions affect system performance. Adding oil separators—rare in internal combustion engine vehicle systems—can improve lubricant management for R744. Virtual prototyping speeds up development, reducing design time and costs. Other challenges include the need for specialized components and materials for high pressure, greater system complexity, and compliance with safety standards and training challenges for technicians regarding transcritical properties and operating pressure.

A comprehensive evaluation under real operating conditions is needed to guide design improvements and ensure successful integration.

7 Conclusions

Efforts to extend electric vehicle driving range and eliminate high-GWP refrigerants have accelerated technological convergence in the automotive sector. R744 has become a promising working fluid in advanced automotive thermal management. This review shows R744-based systems meet current efficiency and sustainability requirements, providing a robust yet complex solution.

The distinct thermodynamic properties of the transcritical R744 cycle present engineering challenges. While these properties improve environmental performance and heating in cold climates, they also cause throttling losses that decrease cooling efficiency in warm conditions. This trade-off has stimulated technological innovation. Solutions such as internal heat exchangers, vapor injection, and expansion work recovery now substantially enhance system performance. In heating mode and under certain operating conditions, R744 systems match or exceed the performance of HFC-based alternatives without requiring auxiliary components such as PTC heaters. A significant advance has been the transition from standalone HVAC units to fully ITMS. In these integrated configurations, the R744 heat pump facilitates energy transfer among the cabin, battery, and powertrain, centralizing energy control and supporting vehicle energy optimization. Despite these improvements, operational challenges persist. High sensitivity to refrigerant charge, complex pressure management, and frost-related issues necessitate advanced predictive control strategies. Ongoing progress in these areas is essential to realize the full potential of R744-based thermal management technology.

In summary, further engineering development is required; however, current evidence indicates that R744-based thermal management is a promising technology for electric vehicles. Continued advancements in cycle design, component engineering, and control strategies will enable electric vehicles to operate efficiently and with low environmental impact in all climates, representing a critical step for the industry's future.

Abbreviations

AC	Air conditioning
ACCU/IHX	Internal heat exchanger with accumulator
ACHP	Air conditioning/heat pump
AI	Artificial intelligence
ANN	Artificial neural network
ASHP	Air-source heat pump
BEV	Battery electric vehicle
BTM	Battery thermal management
CFC	Chlorofluorocarbons
CFD	Computational fluid dynamics
COP	Coefficient of Performance
CTM	Cabin thermal management
EER	Energy efficiency ratio
EEV	Electronic expansion valve (also called EXV)
ESC	Extremum seeking control
ESD	Energy storage device
EV	Electric vehicle
EWR	Expansion work recovery
GWP	Global warming potential
h	enthalpy
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning

ICC	Intermediate cooling compressor
ICE	Internal combustion engine
IGC	Indoor gas cooler
IHEX	Indoor heat exchanger
IHX	Internal heat exchanger
IPLV	Integrated part load value
ITMS	Integrated thermal management system
ML	Machine learning
MPC	Model predictive control
MTM	Motor thermal management
NRC	Normalized refrigerant charge
ODP	Ozone depletion potential
OGC	Outdoor gas cooler
OHEX	Outdoor heat exchanger
OHP	Optimal high pressure (also called optimal discharge pressure)
PCM	Phase change material
PFAS	Polyfluorinated alkyl substances
PI	Proportional, integral
PID	Proportional, integral, derivative
PMV	Predicted mean vote
PTC	Positive temperature coefficient
SEE	System exergy efficiency
SGC	Series gas cooler
SOC	State of charge
SVR	Support vector regression
T	temperature
TC-VRC	transcritical virtual refrigerant charge
TMEF	Thermal management energy consumption factors
TMS	Thermal management system
V2X	Vehicle to everything
VI	Vapor injection
WGC	Water gas cooler
WHR	Waste heat recovery

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Declarations

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