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Refrigerant Performance in Passenger-Car Air-Conditioning Systems: A Comparative Analysis of R-1234yf and R-134a

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Abstract: **The air-conditioning (AC) system of a modern passenger car is a thermodynamically demanding subsystem that consumes 5–20 % of the vehicle's total energy under typical operating conditions. The choice of refrigerant directly determines the system's cooling performance, energy efficiency, and environmental impact. This paper examines the engineering implications of replacing R-134a, the dominant car AC refrigerant from the early 1990s through the mid-2010s, with R-1234yf, the hydrofluoroolefin (HFO) now mandated by international regulations on low global-warming-potential (GWP) refrigerants. The paper describes the architecture and operation of a typical car AC system, formulates the governing thermodynamic equations of the vapor-compression cycle, and synthesizes peer-reviewed experimental data. Drop-in substitution of R-1234yf for R-134a in unmodified car AC hardware reduces cooling capacity by 4–9 %, lowers the coefficient of performance (COP) by 3–7 %, increases refrigerant mass-flow rate by 10–14 %, and lowers compressor discharge temperature by 7–12 K, with the penalty growing at high ambient temperatures. Component-level optimization—particularly the addition of an internal heat exchanger and increased subcooling—can recover most of the lost performance. The paper concludes with a discussion of trifluoroacetic acid (TFA) atmospheric breakdown, proposed PFAS restrictions, and the role of integrated heat-pump systems in electric vehicles.**

Keywords: **car air conditioning, automotive HVAC, R-1234yf, R-134a, HFO refrigerant, vapor-compression cycle, coefficient of performance, electric-vehicle thermal management.**

I. INTRODUCTION

Air conditioning has become a standard, and in many markets a legally required, feature of passenger cars. Beyond passenger comfort, the car AC system performs three distinct safety-related functions: it cools the cabin to a tolerable temperature, removes humidity to prevent fogging of the glass surfaces, and works in conjunction with the heater to defrost the windscreen during cold-weather driving. According to the International Energy Agency, car AC systems consume between 5 % and 20 % of total vehicle energy depending on ambient temperature and driving cycle, with the upper end of that range reached in hot-climate markets such as the Arabian Peninsula, sub-Saharan Africa, and South Asia [1].

From an engineering standpoint, the car AC system is a vapor-compression refrigeration machine adapted to a constrained automotive package: limited under-hood volume, exposure to vibration and thermal cycling, dependence on engine power (or in modern hybrid and electric vehicles, on a high-voltage battery), and a stringent leakage requirement because the refrigerant is sealed for the life of the vehicle. The working fluid—the refrigerant—is the single component that most strongly determines the system's cooling capacity, its electrical or mechanical power demand, and, increasingly, its regulatory status. For more than two decades, that refrigerant was R-134a, a hydrofluorocarbon (HFC) with zero ozone-depletion potential (ODP) but a 100-year global warming potential (GWP) of approximately 1,430 [2].

Because car AC systems leak refrigerant—annual fugitive emissions of 10–15 % of total charge are typical [3]—the cumulative climate impact of a global fleet of more than 1.4 billion R-134a-charged vehicles became unacceptable as climate-policy frameworks tightened. This led directly to a regulatory phase-out of R-134a in new vehicles, beginning with the European Union Mobile Air Conditioning (MAC) Directive 2006/40/EC [4] and culminating with the Kigali Amendment to the Montreal Protocol in 2019 [5]. The dominant industry response was the adoption of R-1234yf, a hydrofluoroolefin with a GWP below 4 and broadly similar thermodynamic properties to R-134a.

This paper provides technical analysis of refrigerant performance in passenger-car AC systems. The objectives are: (i) to describe the architecture and operating principles of the car AC system as it exists in modern vehicles; (ii) to summarize the regulatory and historical context of refrigerant evolution in the automotive industry; (iii) to formulate the governing thermodynamic equations of the car AC vapor-compression cycle and apply them quantitatively to R-134a and R-1234yf; (iv) to synthesize peer-reviewed experimental and simulation findings on comparative performance; and (v) to discuss future challenges, including TFA breakdown products, possible PFAS regulation, and heat-pump-integrated thermal management in electric vehicles.

II. ARCHITECTURE AND OPERATION OF CAR AC SYSTEMS

A. System Layout in the Vehicle

A passenger car's AC system is physically distributed across two regions of the vehicle, connected by sealed refrigerant lines. The high-pressure side of the cycle—the compressor, condenser, and receiver/dryer—is mounted in the engine bay, where it has access to the drive belt (or in electric vehicles, to the high-voltage bus) and to ram-air cooling at the front of the vehicle. The low-pressure side—the thermostatic expansion valve (TXV) and the evaporator—is integrated into the heating, ventilation, and air-conditioning (HVAC) module behind the dashboard, where the cabin blower fan moves recirculated or fresh air across the evaporator coil. Fig. 1 shows this layout schematically.

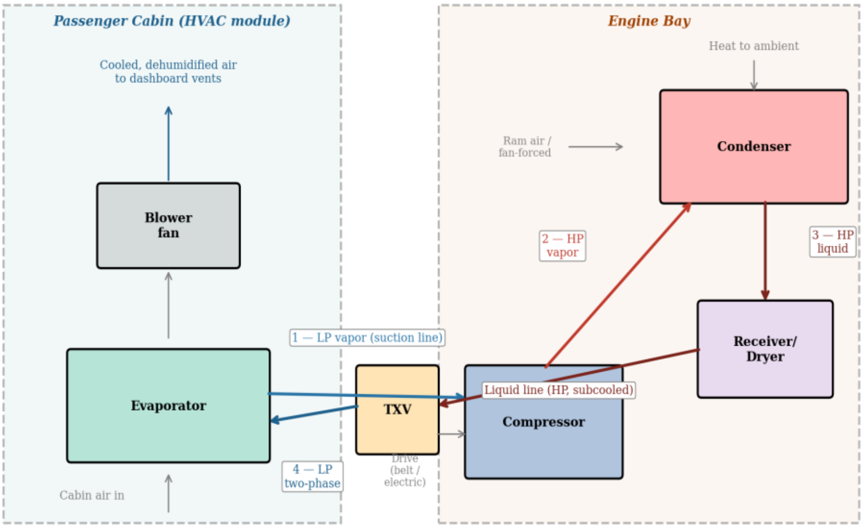

Fig. 1: Schematic of a passenger-car air-conditioning system, showing component layout across the passenger cabin and engine bay, and the refrigerant flow path (states 1→2→3→4→1).

B. Major Components

The AC compressor is the most actively engineered component of the car AC system. Three architectures dominate modern designs: the fixed-displacement reciprocating compressor (used in older or low-cost vehicles); the variable-displacement swash-plate compressor, which adjusts piston stroke through an internal control valve to match the cabin cooling demand without cycling on and off; and the electric scroll compressor, which is now standard in hybrid and battery-electric vehicles. Engine-driven compressors are coupled to the crankshaft pulley by a serpentine belt and engaged through an electromagnetic clutch; electric compressors instead use a permanent-magnet motor powered by the high-voltage bus (typically 200–800 V), which decouples compressor speed from vehicle speed and enables precise modulation.

The condenser is a finned-tube or microchannel heat exchanger mounted at the front of the engine bay, ahead of the engine radiator, where it rejects the cycle's heat load to the ambient airstream. Modern condensers use multi-pass parallel-flow microchannel construction, which provides high surface area within a thin frontal package. Downstream of the condenser, a receiver/dryer (in TXV systems) or accumulator (in fixed-orifice-tube systems) removes residual moisture using a desiccant such as molecular sieve XH-7 or XH-9, filters out particulate contaminants, and provides a liquid reservoir to dampen flow transients.

The expansion device meters refrigerant flow into the evaporator. Most modern car AC systems use an externally equalized thermostatic expansion valve (TXV), which uses a thermal bulb on the suction line to modulate the orifice opening and maintain a near-constant superheat at the evaporator outlet. Some economy vehicles use a fixed-orifice tube (FOT), simpler and cheaper but less efficient at part-load conditions. The evaporator itself, also typically a microchannel heat exchanger, sits inside the HVAC plenum where the cabin blower fan forces 200–500 m^3/h of air through it. As refrigerant boils inside the evaporator tubes, latent heat is absorbed from the cabin airstream, cooling and dehumidifying it before delivery to the dashboard vents.

C. Operating Cycle and Control

The car AC cycle operates at design-point pressures of approximately 0.20–0.35 MPa on the low (suction) side and 1.2–2.0 MPa on the high (discharge) side, with the exact values determined by ambient temperature, vehicle speed, and cabin cooling demand. Cycle control is managed by the vehicle's electronic climate-control unit, which interprets cabin temperature setpoints, sun-load sensors, ambient temperature, and refrigerant pressures to drive the compressor clutch (or motor inverter), the blower fan speed, the air-mix damper, and the recirculation flap. Modern systems also include a high-pressure cut-out switch that disengages the compressor if discharge pressure exceeds a safe limit (typically 3.0 MPa for R-1234yf systems).

III. REFRIGERANT EVOLUTION IN THE AUTOMOTIVE INDUSTRY

Refrigerant choice in car AC systems has undergone two major transitions in the past four decades, each driven by environmental science and policy. The first transition, from R-12 (dichlorodifluoromethane, CCl_2F_2) to R-134a, was triggered by the 1987 Montreal Protocol, which mandated the phase-out of chlorofluorocarbons (CFCs) on the basis of their ozone-depletion potential. R-12 systems—standard in cars from the 1950s through the 1980s—were progressively retired through the 1990s, with R-134a becoming dominant in new vehicles by the 1995 model year in North America and slightly later in Europe and Asia. R-134a offered zero ODP, broadly similar thermodynamic properties to R-12, and could be retrofitted into existing vehicles with modified hoses, lubricant changes (from mineral oil to PAG), and minor service-port adjustments.

The second transition—from R-134a to R-1234yf—was triggered by climate-change concerns rather than ozone depletion. The European Union Directive 2006/40/EC [4] prohibits the use of refrigerants with GWP > 150 in air-conditioning systems of new vehicle types receiving type-approval from 1 January 2011, and in all new vehicles sold from 1 January 2017. The United States EPA's SNAP program (40 CFR Part 82) similarly delisted R-134a from new light-duty vehicles starting in model year 2021. The Kigali Amendment to the Montreal Protocol [5] further committed signatory nations to a phased reduction in HFC consumption. R-1234yf emerged as the dominant choice, offering a 100-year GWP below 4, drop-in compatibility with most R-134a system architectures (with revised hoses, service ports, and lubricants), and operating pressures within the same range. Its principal disadvantages—mild flammability (ASHRAE A2L) and the production of trifluoroacetic acid (TFA) on atmospheric breakdown—are discussed in Section VII.

IV. LITERATURE REVIEW

The car AC refrigerant transition has generated a substantial peer-reviewed literature over the past decade, organized below into four categories: thermodynamic property characterization, drop-in performance evaluation, component-level optimization, and hot-climate performance assessment.

A. Thermodynamic Property Characterization

Reliable equations of state are foundational to engineering analysis. The reference correlation for R-1234yf, developed by Richter, McLinden, and Lemmon [6], uses a Helmholtz-energy formulation fitted to experimental $P–\rho–T$, vapor-pressure, speed-of-sound, and isobaric heat-capacity data, and is now embedded in NIST REFPROP 10. The corresponding reference correlation for R-134a was published earlier by Tillner-Roth and Baehr [7]. Both correlations show that R-1234yf has a critical temperature of 94.7 °C and critical pressure of 3.382 MPa, both lower than R-134a (101.06 °C, 4.059 MPa). The latent heat of vaporization at 0 °C is approximately 163 kJ/kg for R-1234yf and 199 kJ/kg for R-134a—an 18 % deficit that has direct implications for the required mass flow rate in a given car AC system.

B. Drop-In Performance Studies in Car AC Hardware

Navarro-Esbrí et al. [8] carried out one of the most-cited drop-in comparisons using a vapor-compression test rig representative of car AC operating conditions. They reported that R-1234yf delivered a cooling capacity 9 % lower and a COP 7 % lower than R-134a under standard ARI conditions, with discharge temperatures 6.5 K lower. Comparable findings were reported by Lee and Jung [9], Cho et al. [10], and Daviran et al. [11], with COP penalties typically in the range of 3–7 %. Zilio et al. [12] extended the analysis to a complete car AC system with the compressor, condenser, expansion valve, and evaporator from a production passenger vehicle, finding that the cooling-capacity gap narrows significantly when components are optimized for R-1234yf.

C. Component Optimization for Car AC Systems

Pottker and Hrnjak [13] demonstrated that increasing condenser subcooling from 5 K to 10 K provides up to 6 % COP gain for R-1234yf, partially offsetting the cooling-capacity deficit. Microchannel heat-exchanger geometries with smaller hydraulic diameters and increased frontal area were identified by Jang et al. [14] as effective measures for handling the higher mass flow rate that R-1234yf requires. On the compressor side, Direk et al. [15] tested both reciprocating and scroll compressors and concluded that scroll architectures are particularly well suited to R-1234yf, due to their lower internal leakage at the higher mass flow demand.

D. Hot-Climate Performance and Research Gap

Most published work on R-1234yf was conducted under European or North American test conditions (25–35 °C ambient). Considerably less data exist for hot-climate markets where cars routinely operate at 45–50 °C. Recent investigations by Daviran et al. [11] and Mohamed et al. [16] suggest that the COP gap between R-1234yf and R-134a widens at high condenser temperatures, primarily because R-1234yf's lower critical temperature causes it to approach the critical point and exhibit non-ideal behaviour. This represents a significant research gap, particularly given that hot-climate regions are also high-volume car markets.

V. THERMODYNAMIC ANALYSIS OF THE CAR AC CYCLE

A. The Vapor-Compression Cycle in Car AC Systems

The car AC cycle is an idealized subcritical vapor-compression refrigeration cycle with four thermodynamic state points: state 1, saturated (or slightly superheated) vapor leaving the evaporator at low pressure P_e; state 2, superheated high-pressure vapor leaving the compressor; state 3, subcooled liquid leaving the condenser at high pressure Pc; and state 4, two-phase mixture entering the evaporator after isenthalpic expansion through the TXV. Fig. 2 shows this cycle on the pressure–enthalpy (P–h) plane for both refrigerants. The smaller saturation dome of R-1234yf, lower critical pressure, and reduced enthalpy of vaporization are immediately visible and directly explain the comparative performance behaviour analyzed in Section VI.

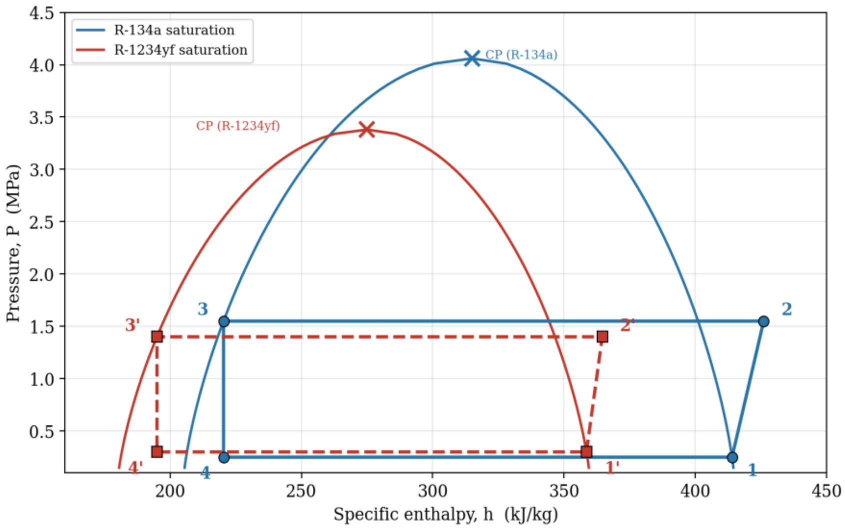

Fig. 2: Schematic pressure–enthalpy (P–h) diagrams of the ideal vapor-compression cycle for R-134a (solid) and R-1234yf (dashed).

B. Governing Equations

Applying steady-state energy balances to each component of the car AC cycle, the cooling capacity (in kW) delivered to the cabin air is:

$$\dot{Q}_{evap} = \dot{m}\,(h_1 - h_4) \quad (1)$$

where $\dot{m}$ is the refrigerant mass flow rate (kg/s) and h_i are specific enthalpies (kJ/kg) at the labelled state points. The mechanical or electrical power consumed by the compressor is:

$$\dot{W}_{comp} = \dot{m}\,(h_2 - h_1) \quad (2)$$

Real compressors do not achieve isentropic compression. The isentropic efficiency η_{is} relates the ideal (isentropic) work h_{2s} to the actual work delivered to the refrigerant:

$$\eta_{is} = (h_{2s} - h_1) / (h_2 - h_1) \quad (3)$$

The coefficient of performance (COP), the most important figure of merit for any refrigeration cycle and the central metric used to compare R-134a and R-1234yf in car AC service, is the ratio of useful cooling delivered to the cabin to mechanical work consumed by the compressor:

$$COP = \dot{Q}_{evap} / \dot{W}_{comp} = (h_1 - h_4) / (h_2 - h_1) \quad (4)$$

Heat rejected at the condenser to the ambient airstream is given by:

$$\dot{Q}_{cond} = \dot{m}\,(h_2 - h_3) \quad (5)$$

Conservation of energy requires $\dot{Q}$_cond = $\dot{Q}$_evap + $\dot{W}$_comp. A fourth quantity of practical importance for car AC compressor sizing is the volumetric refrigerating effect q_v (kJ/m³), which represents the cooling delivered per unit volume of suction-line vapor:

$$q_v = (h_1 - h_4) / v_1 \quad (6)$$

where v_1 is the specific volume of suction vapor (m³/kg). At identical evaporator and condenser temperatures, R-1234yf exhibits a 5–8 % lower q_v than R-134a, which directly translates into a need for higher compressor displacement (or higher compressor speed) to deliver equivalent cabin cooling capacity.

C. Comparison of Refrigerant Properties

TABLE I summarizes the principal thermophysical and environmental properties of R-134a and R-1234yf relevant to car AC system design. The differences in critical temperature, latent heat of vaporization, and vapor density together account for most of the performance differences observed in service.

TABLE I: KEY THERMOPHYSICAL AND ENVIRONMENTAL PROPERTIES OF R-134a AND R-1234yf

Property	**R-134a**	**R-1234yf**
Chemical formula	CH_2FCF_3	$CF_3CF=CH_2$
Molecular mass (g/mol)	102.03	114.04
Boiling point at 101.3 kPa (°C)	−26.07	−29.45
Critical temperature (°C)	101.06	94.70
Critical pressure (MPa)	4.059	3.382
Latent heat at 0 °C (kJ/kg)	199	163
Vapor density at 0 °C (kg/m³)	14.4	17.7
100-year GWP (AR5)	1,430	< 4
ODP	0	0
ASHRAE safety class	A1	A2L
Atmospheric lifetime	13.4 yr	10.5 days

Sources: NIST REFPROP 10; Myhre et al. [17]; Richter et al. [6].

VI. COMPARATIVE PERFORMANCE IN CAR AC SERVICE

A. Drop-In Performance Penalty

Fig. 3 summarizes the consensus comparative performance of R-1234yf relative to R-134a in unmodified, drop-in car AC hardware, derived from a meta-analysis of the studies cited in Section IV. R-1234yf exhibits approximately a 7 % lower cooling capacity, a 5 % lower COP, a 13 % higher mass flow rate, and a 7–12 K lower compressor discharge temperature. The compressor work itself is only marginally lower (−2 %), as the slight reduction in pressure ratio is offset by the higher mass-flow demand.

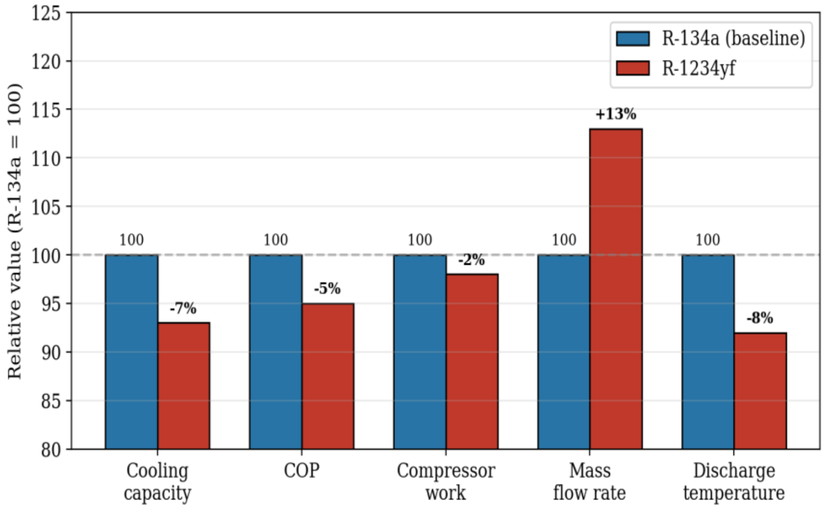

Fig. 3: Representative performance comparison of R-1234yf vs. R-134a in drop-in car AC systems (averaged from published literature).

The lower discharge temperature is one of the few thermodynamic advantages of R-1234yf in car AC service: it reduces thermal stress on compressor seals and on the lubricant, potentially extending compressor service life. However, this benefit is partially offset by the higher operating pressures developed at high ambient temperatures, where R-1234yf approaches its critical point sooner than R-134a.

B. Effect of Ambient Temperature on Car AC Performance

The performance gap between the two refrigerants is not constant; it widens with increasing ambient temperature, as shown in Fig. 4. At T_{amm} = 25 °C, COP values of approximately 4.2 (R-134a) and 4.0 (R-1234yf) are achievable in well-designed car AC systems—a difference of roughly 5 %. At T_{amm} = 50 °C, a routine summer condition for cars operating in the Arabian Peninsula and South Asia, COP falls to approximately 2.8 for R-134a and 2.45 for R-1234yf, an absolute drop of nearly 13 %. This nonlinear behaviour is a direct consequence of R-1234yf's lower critical temperature.

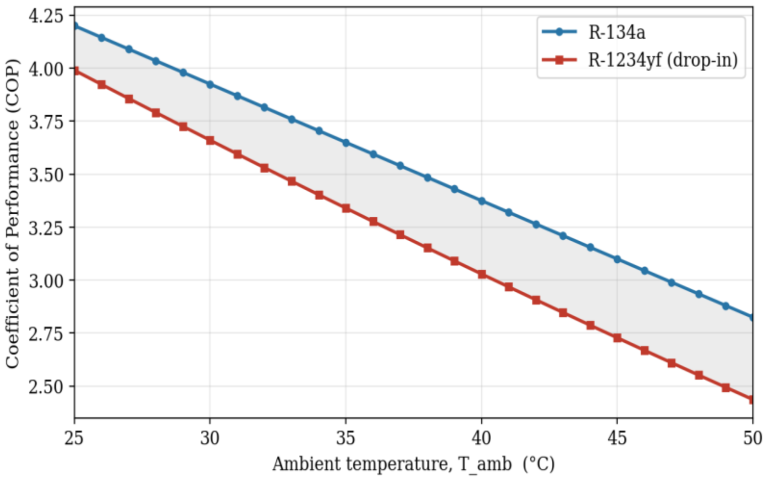

Fig. 4: Effect of ambient temperature on COP (representative trend from compiled experimental studies).

C. Recovering Performance Through Car AC System Design

Most of the drop-in performance penalty can be recovered through targeted modifications to the car AC system. The single most effective intervention is the addition of an internal heat exchanger (IHX) between the liquid line (state 3) and the suction line (state 1). The IHX increases evaporator subcooling and provides controlled superheating of the suction vapor, which raises q_v. With a properly sized IHX, COP gains of 3–6 % are typical, and Pottker and Hrnjak [13] demonstrated experimentally that a coaxial IHX restored R-1234yf COP to within 1.5 % of R-134a in a representative car AC system. Other effective modifications include larger microchannel condensers, larger TXV orifice areas, and variable-displacement or electric scroll compressors with control logic optimized for R-1234yf's pressure-temperature characteristics. By 2024, R-1234yf had been adopted by virtually all major automotive original-equipment manufacturers (OEMs) for new passenger-vehicle platforms in the European Union and North America, with more than 100 million vehicles globally now operating on R-1234yf [18].

VII. FUTURE CHALLENGES IN CAR AC REFRIGERANT SELECTION

A. Trifluoroacetic Acid (TFA) Atmospheric Breakdown

Although R-1234yf has a very short atmospheric lifetime (about 10.5 days), its breakdown is precisely what produces a renewed environmental concern. Under tropospheric oxidation by hydroxyl (OH) radicals, R-1234yf decomposes to trifluoroacetyl fluoride (CF_3COF), which subsequently hydrolyzes to trifluoroacetic acid (TFA, CF_3COOH). TFA is environmentally persistent, bioaccumulative in some aquatic ecosystems, and is removed from the atmosphere primarily by wet deposition [19]. The German Federal Environment Agency reported in 2023 that TFA from car AC refrigerants is a significant non-point source contributing to rising background TFA concentrations in European surface waters [20]. This may impose new constraints on R-1234yf use in the medium term.

B. PFAS Regulation

A more immediate regulatory threat is the 2023 European Chemicals Agency (ECHA) proposal to restrict per- and polyfluoroalkyl substances (PFAS) [21]. Under the proposed definition, R-1234yf and many HFO refrigerants qualify as PFAS due to their fully fluorinated carbon centers. If enacted in its current form, the restriction could impose a phase-out period as short as 5–13 years following final adoption, which would force a second car AC refrigerant transition within a single decade. Industry has lobbied for derogations, citing the absence of viable substitutes for safety-critical car applications, but the regulatory outcome remains uncertain.

C. Electric Vehicles and Heat-Pump Integration

The accelerating shift toward battery-electric vehicles is reshaping car AC system requirements. Unlike internal-combustion vehicles, electric cars cannot use waste engine heat for cabin warming; they must produce all heat electrically. Resistive heaters work but consume valuable battery energy and reduce winter driving range by 30–40 %. Integrated heat-pump systems, which use a reversible vapor-compression cycle to either heat or cool the cabin and the battery pack from a single refrigerant loop, can reduce that range penalty to 10–15 %. R-1234yf is suitable for moderate-climate heat-pump operation but loses efficiency rapidly below −10 °C. R-744 (CO_2, GWP = 1) operates effectively to −30 °C and is now used in heat-pump systems on certain BMW iX and Volkswagen ID-series models, despite the high operating pressures (8–14 MPa) it requires. As electric vehicles capture a larger share of the new-car market, the long-term dominance of R-1234yf in car AC service may give way to a more diversified refrigerant landscape.

VIII. CONCLUSION

The transition from R-134a to R-1234yf in passenger-car air-conditioning systems represents one of the largest refrigerant changeovers in industrial history, driven by clearly stated regulatory targets and an order-of-magnitude reduction in life-cycle climate impact (GWP from 1,430 to less than 4). Comparative analysis demonstrates that R-1234yf delivers approximately 3–7 % lower COP and 4–9 % lower cooling capacity than R-134a in unmodified drop-in car AC configurations, with the gap widening at the high ambient temperatures characteristic of hot-climate markets. The penalty arises from R-1234yf's lower latent heat of vaporization, lower critical temperature, and lower vapor density, all of which require higher refrigerant mass flow rate to achieve equivalent cabin cooling.

Most of this penalty can be recovered through component-level optimization of the car AC system: internal heat exchangers, microchannel condensers, increased subcooling, and properly sized variable-displacement or electric scroll compressors can restore R-1234yf COP to within 1–2 % of R-134a. Industrial adoption is now nearly universal in regulated markets, with more than 100 million cars globally operating on R-1234yf. Looking forward, two issues may force a further refrigerant transition within the next 5–15 years: the persistent environmental presence of TFA and the proposed European PFAS restrictions. Continued research and engineering effort should focus on (i) characterization of car AC performance under hot-climate operating conditions; (ii) maturation of trans-critical R-744 systems for cost-competitive integration into electric vehicles; (iii) life-cycle climate-performance (LCCP) analyses of competing refrigerant options; and (iv) charge-minimization techniques that may eventually permit hydrocarbon refrigerants in passenger cars.

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