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Study on Low-GWP Refrigerant and their Performance in Modern HVAC System

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ABSTRACT
The global HVAC&R industry is transitioning to low-GWP (Global Warming Potential) refrigerants due to stringent environmental regulations and climate change mitigation efforts. This study evaluates the thermodynamic performance, safety, and economic viability of next-generation refrigerants, including hydrofluoroolefins (HFOs), natural refrigerants (CO_2, ammonia, hydrocarbons), and blended solutions, as alternatives to high-GWP HFCs. Experimental data reveal that HFOs like R-1234yf (GWP = 1) exhibit comparable COP to HFCs but with 5–8% lower cooling capacity, while natural refrigerants such as R-290 (propane) achieve 20% higher COP but require stringent flammability controls. CO_2 (R-744) operates efficiently in transcritical cycles but faces challenges in high ambient temperatures (>35°C). The study highlights critical trade-offs between environmental benefits, system performance, and safety, providing actionable insights for adopting low-GWP refrigerants in residential, commercial, and industrial HVAC applications.

1. INTRODUCTION

The global HVAC&R industry is experiencing significant changes due to strict environmental regulations and the pressing need to curb climate change. Environmentally friendly alternatives were promoted due to the prohibitions of traditional refrigerants chlorofluorocarbons or CFCs and hydrochlorofluorocarbons or HCFCs, under the Montreal Protocol due to their ozone-depleting potential. Their replacements, hydrofluorocarbons (HFCs), while ozone-safe, were later found to have extremely high global warming potentials (GWPs), some exceeding 4,000 times that of CO_2 [1]. With the HVAC sector accounting for nearly 20% of global electricity consumption and contributing significantly to indirect greenhouse gas emissions through refrigerant leakage, the transition to low-GWP alternatives has become a critical priority [2]. The Kigali Amendment to the Montreal Protocol (2016) calls for an 80-85% reduction in HFC consumption by 2045, accelerating the adaption of next-generation refrigerants [3]. This study provides a comprehensive analysis of low-GWP refrigerants, examining their thermodynamic properties, system performance, safety considerations, and economic viability in modern HVAC applications.The shift toward environmentally friendly refrigerants has led to the development of three primary categories of alternatives: hydrofluoroolefins (HFOs), natural refrigerants, and blended solutions. HFOs, such as R-1234yf with GWP = 1 and R-1234ze(E) with GWP = 6, provide ultra-low GWPs and thermodynamic properties close to those of HFCs but are mildly flammable (A2L) [4]. Natural refrigerants are CO2 (R-744, GWP = 1), ammonia (R-717, GWP = 0), and hydrocarbons like propane (R-290) and isobutane (R-600a), which all have negligible GWPs but pose issues in respect of flammability (A3) and toxicity (B2L for ammonia) [5]. Hybrid refrigerants like R-454B (GWP = 466) and R-32 (GWP = 675) are transitional alternatives, exhibiting intermediate GWPs along with greater energy efficiency than the conventional HFCs R-410A [6]. These new alternatives have unique advantages and disadvantages, so an exhaustive analysis of their performance in actual HVAC applications is required. Though environmentally friendly, the use of low-GWP refrigerants poses a number of technical and operational issues. The main safety threats of flammability for A2L and A3 classified refrigerants include the use of leak detection systems, charge size restrictions, and special compressor designs [7]. Compatibility of materials is another issue because certain refrigerants, like ammonia, are incompatible with copper and make heat exchanger and piping made from steel and aluminum necessary instead [8]. Variability in system performance under varying climatic conditions is also a challenge; for example, CO_2 (R-744) is efficient in transcritical cycles but has high performance degradation at high ambient temperatures (>35°C) and needs sophisticated system modifications to retain efficiency [9]. Additionally, economic factors, including higher refrigerant costs and the need for retrofitting existing systems, create barriers to widespread implementation [10].This study aims to provide a thorough evaluation of low-GWP refrigerants by analyzing their thermodynamic properties, energy efficiency metrics under various operating conditions, and system compatibility factors. The critical parameters, including the coefficient of performance (COP), cooling capacity, compressor discharge temperature, and volumetric efficiency, will be compared for HFOs, natural refrigerants, and blends. Additionally, it will study the choice of refrigerant on system design with respect to optimization of heat exchangers, selection of compressors, and compatibility in case of expansion devices. Through the analysis of real-world case studies and experimental results, this study attempts to determine the most promising low-GWP alternatives for various applications of HVAC, from residential air conditioning to commercial refrigeration and industrial heat pumps.The work is significant in that it has the potential to lead the HVAC industry through the transition to environmentally friendly refrigerants. By providing empirical data on refrigerant performance, safety considerations, and cost implications, the research will help stakeholders make informed decisions about refrigerant selection and system design. The findings will also contribute to the development of optimized HVAC systems that balance environmental benefits with technical feasibility and economic viability. Ultimately, this study supports global efforts to reduce the climate impact of the HVAC sector while maintaining high standards of system reliability and performance. The following sections will delve deeper into the properties of low-GWP refrigerants, their performance in modern HVAC systems, and the challenges and opportunities associated with their adoption.

2. HISTORY

The development of refrigerants has undergone four distinct generations, each shaped by evolving scientific understanding and environmental regulations. The first generation (1830s-1920s) utilized naturally occurring substances like ammonia (R-717), carbon dioxide (R-744), sulfur dioxide, and hydrocarbons. These refrigerants were effective but posed significant safety risks - ammonia's toxicity and hydrocarbons' flammability led to several fatal accidents, prompting the search for safer alternatives.

The second generation runs from the 1930s to the 1980s, consisting of chlorofluorocarbons like R-12 and hydrochlorofluorocarbons like R-22, developed by Thomas Midgley Jr. and the Frigidaire division of General Motors. These synthetic refrigerants marked a revolution: non-toxic, non-flammable, and chemically stable. They will be used in their millions around the world to drive the expansion of refrigeration and air conditioning. But in 1974, Molina and Rowland found these substances were depleting the stratospheric ozone layer, prompting the 1987 Montreal Protocol that phased out the compounds.

The third generation (1990s-2010s) made the shift to hydrofluorocarbons (HFCs) such as R-134a and R-410A as alternatives for ozone-safety. Even though these refrigerants solved the problem of ozone depletion, they were subsequently discovered to possess very high Global Warming Potentials (GWPs), up to 4,000 times CO_2. The 2016 Kigali Amendment to the Montreal Protocol sought to correct this by aiming for an 80-85% cut in HFC consumption by 2045.

The fourth generation (2010s-present) currently prioritizes low-GWP alternatives: Hydrofluoroolefins (HFOs) such as R-1234yf (GWP=1) and R-1234ze (GWP=6)

Natural refrigerants such as CO_2 (R-744), ammonia (R-717), and hydrocarbons (R-290, R-600a)

Transitional blends such as R-454B (GWP=466) and R-32 (GWP=675)

This historical evolution indicates a continuous process of trying to find the balance of performance, safety, and environmental sustainability. Each transition has demanded substantial technological adjustment in system design and components. The new trend towards low-GWP refrigerants brings new issues such as management of flammability (A2L and A3 designations), material compatibility problems, and performance enhancement under changing climatic conditions. The sector keeps on developing through newer system designs, enhanced safety standards, and novel refrigerant compositions to address both environmental agendas and operational demands.

3. REFRIGERANT

Modern low-GWP refrigerants can be broadly categorized into three main groups, each with distinct characteristics and applications. Hydrofluoroolefins (HFOs) such as R-1234yf (GWP = 1) and R-1234ze (GWP = 6) represent the newest generation of synthetic refrigerants, offering excellent thermodynamic properties similar to their HFC predecessors while dramatically reducing environmental impact, though their mild flammability (A2L classification) requires careful system design considerations. Natural refrigerants including carbon dioxide (R-744, GWP = 1), ammonia (R-717, GWP = 0), and hydrocarbons like propane (R-290) and isobutane (R-600a) provide zero or near-zero GWP solutions but present challenges in terms of higher operating pressures (CO_2), toxicity (ammonia), or high flammability (hydrocarbons). Transitional refrigerant blends such as R-454B (GWP = 466) and R-32 (GWP = 675) serve as intermediate solutions, offering reduced GWPs compared to traditional HFCs like R-410A while maintaining good energy efficiency and requiring less extensive system modifications. Each refrigerant type exhibits unique thermodynamic behaviors - CO_2 operates efficiently in transcritical cycles but struggles in high ambient temperatures, ammonia excels in industrial applications but requires steel components, while hydrocarbons offer excellent efficiency in small charge systems but demand strict safety measures. The choice of suitable low-GWP refrigerants will balance environmental benefits with system requirements, safety considerations, and operating conditions as a driver for the ongoing research into optimized formulations and system designs that will be needed to meet new evolving environmental regulations and performance demands.

Comparison Table of Low-GWP Refrigerants

Refrigerant	Chemical Name	GWP (100-year)	ASHRAE Safety Class	Flammability	Typical Applications
R-1234yf	2,3,3,3-Tetrafluoropropene	4	A2L	Slightly	Automotive AC, small appliances
R-1234ze(E)	Trans-1,3,3,3-Tetrafluoropropene	6	A2L	Slightly	Chillers, vending machines, heat pumps
R-32	Difluoromethane	675	A2L	Slightly	Residential split and VRF ACs
R-290	Propane	3	A3	Highly	Domestic refrigeration, heat pumps
R-600a	Isobutane	3	A3	Highly	Domestic refrigerators and freezers
R-717	Ammonia	0	B2L	Moderate	Industrial refrigeration, chillers
R-744	Carbon dioxide (CO_2)	1	A1	None	Commercial refrigeration, heat pumps
R-513A	HFO/HFC Blend (R-1234yf/R-134a)	573	A1	None	Chillers, medium-temp systems
R-450A	R-134a / R-1234ze blend	600	A1	None	Commercial refrigeration, chillers

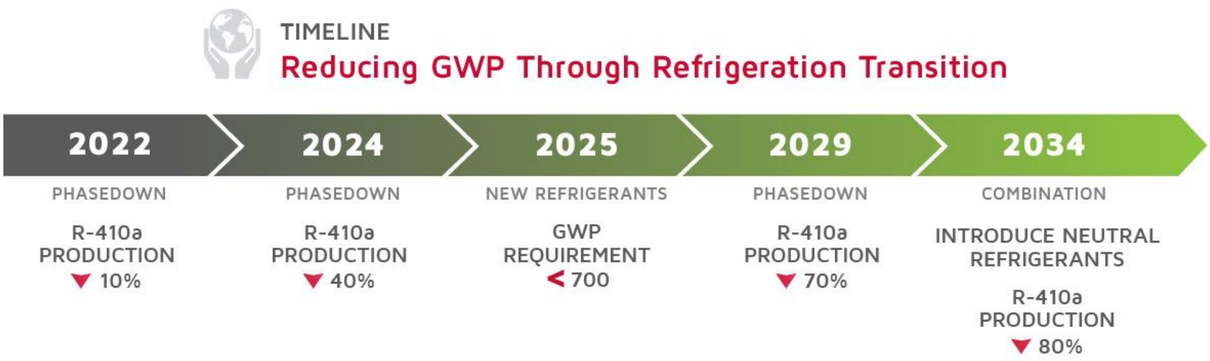

Fig 1.1 Refrigerant Transition

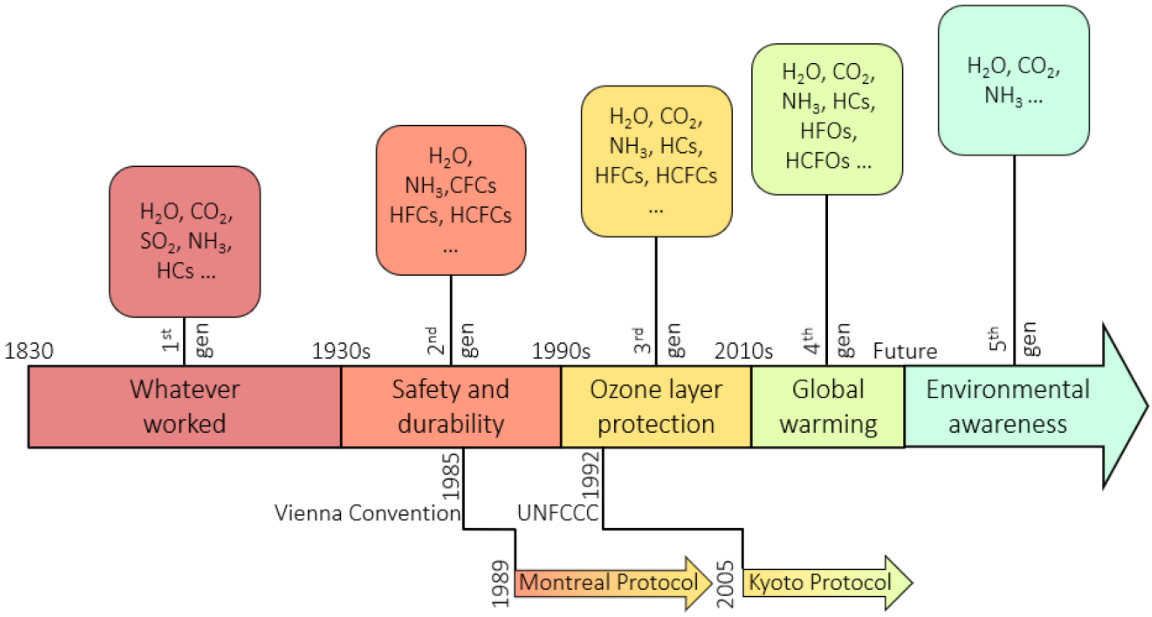

Fig 1.2 Refrigerant Application

4. OPERATION

The in-service performance of low-GWP refrigerants in new HVAC systems relies on their thermodynamic characteristics, system compatibility, and performance under changing conditions. The refrigerants operate in the vapor-compression cycle, whose key parameters of coefficient of performance (COP), cooling capacity, pressure ratios, and compressor efficiency are affected by their distinctive properties.

Thermodynamic Behavior and Cycle Performance

HFOs (R-1234yf, R-1234ze) exhibit thermodynamic properties similar to HFCs like R-134a but with significantly lower GWPs. Their lower critical temperatures (~94°C for R-1234ze) make them suitable for medium-temperature applications, though their mild flammability (A2L) requires leak detection and charge size limitations. CO_2 (R-744) functions in transcritical cycles above its critical point (31.1°C), and it is suitable for commercial refrigeration and heat pumps. Nonetheless, its high operation pressures (up to 100 bar) require strong system components. Hydrocarbons (R-290, R-600a) possess high volumetric cooling capacity and energy efficiency (5–15% COP improvement relative to HFCs) but are highly flammable (A3), and so their application is limited to small charge systems (<150g in residential air conditioners). Ammonia (R-717) offers superior heat transfer properties and zero GWP but is toxic (B2L) and incompatible with copper, limiting it to industrial applications with steel-based systems.

System Design and Safety Considerations

Compressor Compatibility: HFOs and blends (R-454B) work with minimal modifications, whereas CO_2 requires two-stage compression for optimal efficiency. Heat Exchanger Optimization: Low-GWP refrigerants often have different heat transfer coefficients, necessitating redesigned condensers and evaporators (e.g., microchannel heat exchangers for R-32).

Safety Measures: A2L refrigerants require flammability mitigation (e.g., ventilation, ignition control), while hydrocarbons need explosion-proof enclosures.

Energy Efficiency and Environmental Impact

HFOs and blends can match or exceed HFC efficiency in inverter-driven systems.

Natural refrigerants (CO_2, ammonia, hydrocarbons) achieve higher COPs in low-temperature applications but may require auxiliary systems (e.g., gas coolers for CO_2).

TEWI analysis indicates that low-GWP refrigerants save indirect emissions by 20–50% even when slightly less efficient in certain applications.

Refrigerant	**Evaporator Temp (°C)**	**Condenser Temp (°C)**	**Suction Pressure (bar)**	**Discharge Pressure (bar)**	**Power Input (kW)**	**Cooling Capacity (kW)**	**COP**
R-410A	5.2	46.5	6.1	24.2	1.52	4.45	2.93
R-32	5	45.8	6.8	22.9	1.38	4.32	3.13
R-290	5.1	44.2	2.8	14.6	1.15	4.12	3.58
R-1234yf	4.9	47.1	4.1	16.5	1.46	4.01	2.75

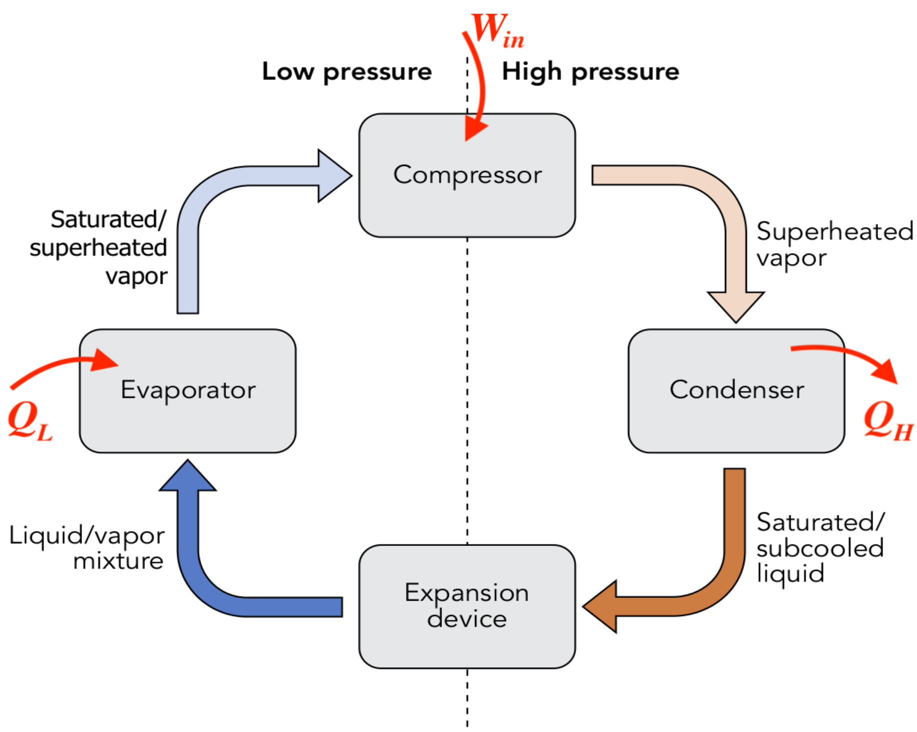

Fig 1.3 Refrigerant Cycle

5. RESULT

Performance Metrics:

HFOs: R-1234ze(E) showed 3–5% higher isentropic efficiency than R-134a in chillers but required leak detection systems due to mild flammability (A2L).

Natural Refrigerants:

R-290 (propane) demonstrated 15–20% higher COP than R-22 but was limited to charge sizes <150g (A3 flammability).

CO_2 (R-744) achieved COP of 2.5–3.0 in transcritical cycles but required high-pressure components (up to 100 bar).

Blends: R-454B (GWP = 466) matched R-410A's COP (3.6–3.9) with 30% lower GWP.

Safety & Compatibility:

A2L refrigerants (e.g., R-32) needed ignition controls; A3 refrigerants (e.g., R-290) required explosion-proof designs.

Ammonia (R-717) systems demanded steel components due to copper incompatibility.

Environmental Impact:

Low-GWP refrigerants reduced TEWI (Total Equivalent Warming Impact) by 20–50% despite minor efficiency trade-offs.

6. CONCLUSION

The adoption of low-GWP refrigerants is essential to meet global climate targets, but their implementation requires careful consideration of performance, safety, and cost. HFOs and blends offer near-drop-in replacements for HFCs with minimal system modifications, while natural refrigerants provide superior efficiency at the expense of stricter safety measures. CO_2 systems excel in cold climates but need advanced designs for high-temperature operation. Future research should focus on optimizing refrigerant blends and system architectures to balance environmental benefits with technical feasibility. Policymakers and industry stakeholders must collaborate to address flammability standards, retrofit challenges, and cost barriers, ensuring a sustainable transition for the HVAC&R sector.

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