iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** VIII **Month of publication:** August 2025

DOI: https://doi.org/10.22214/ijraset.2025.73514

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VIII Aug 2025- Available at www.ijraset.com

A Comprehensive Review on Low-GWP HFO Refrigerants and Subcooling Techniques in Vapor Compression Refrigeration Systems

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Abstract: The global transition toward environmentally sustainable technologies has intensified the research and development of low-global warming potential (GWP) refrigerants and performance-enhancing techniques in vapor compression refrigeration (VCR) systems. Among various candidates, hydrofluoroolefins (HFOs) have emerged as leading alternatives to hydrofluorocarbons (HFCs) due to their favorable thermophysical properties and negligible ozone depletion potential (ODP). Concurrently, subcooling strategies such as dedicated mechanical subcooling (DMS), condensate-assisted subcooling (CAS), and nanoparticle-enhanced methods are being investigated to enhance the coefficient of performance (COP) and energy efficiency of VCR systems. This review comprehensively evaluates 27 recent research works that span drop-in replacement studies, system-level simulations, subcooling configurations, and life-cycle environmental assessments. The findings collectively highlight the performance trade-offs, system adaptability, and long-term viability of low-GWP refrigerants like R1234yf, R1234ze(E), and R513A, as well as the role of subcooling in mitigating energy and exergy losses. This synthesis serves as a foundation for researchers and engineers aiming to design efficient and sustainable refrigeration systems aligned with global climate objectives.
Keywords: Hydrofluoroolefins (HFOs), Low-GWP Refrigerants, Subcooling Techniques, Vapor Compression Refrigeration (VCR), Energy Efficiency, R1234ze(E)

I. INTRODUCTION

Climate change and environmental degradation have accelerated global efforts to phase down high-GWP refrigerants in compliance with international accords such as the Kigali Amendment to the Montreal Protocol. Traditional refrigerants like R134a and R410A, while thermodynamically efficient, contribute significantly to greenhouse gas emissions. In response, research has shifted toward low-GWP alternatives, notably hydrofluoroolefins (HFOs), which combine minimal environmental impact with promising thermodynamic profiles.

Parallel to refrigerant innovation, subcooling techniques are gaining prominence for enhancing the energy efficiency of vapor compression refrigeration (VCR) systems. Techniques such as dedicated mechanical subcooling (DMS), integrated subcooling systems, and condensate-assisted methods have demonstrated measurable gains in COP and system reliability.

This paper presents a detailed and structured review of 27 peer-reviewed studies focused on two major thrusts: (i) the application and evaluation of low-GWP HFO refrigerants, especially R1234ze(E), R1234yf, and blends like R513A, and (ii) the implementation and comparative performance of advanced subcooling strategies in VCR systems. The review is organized to critically assess the thermodynamic performance, environmental metrics, compatibility, and limitations associated with each intervention, offering a roadmap for future development of sustainable cooling technologies.

II. LITERATURE REVIEW

The literature on low-GWP refrigerants and subcooling strategies in vapor compression refrigeration systems (VCRS) is extensive and multifaceted. This section categorizes and synthesizes 27 pivotal studies, encompassing both experimental and theoretical analyses of hydrofluoroolefins (HFOs), refrigerant blends, and advanced subcooling methods aimed at improving energy performance and environmental sustainability.

Belman-Flores et al. [1] conducted an experimental study assessing R513A, R516A, and R1234ze(E) as drop-in replacements for R134a in household refrigeration. R1234ze(E) emerged as the most promising candidate, achieving a 13% increase in COP and a 5% reduction in Total Equivalent Warming Impact (TEWI), emphasizing its suitability for domestic applications.

Solanki et al. [2] evaluated a dedicated mechanical subcooling (DMS) cycle using R134a, reporting a 9.5% increase in COP and a 15.52% reduction in electricity usage. The study emphasized the environmental benefits of the DMS-VCRS configuration, highlighting its viability in high-capacity commercial refrigeration.

Prasad et al. [3] analyzed multiple refrigerants and blends through experimental and simulation approaches. The R32/R41/R1234ze(E) blend demonstrated a 27% higher cooling rate than R134a, while RE170 excelled in heat transfer metrics, underscoring the potential of blended low-GWP refrigerants.

Agarwal et al. [4] focused on mechanically subcooled systems using R1234yf and R1234ze. R1234ze outperformed both R134a and R1234yf in terms of COP and exergetic efficiency, with condenser and evaporator identified as key sites for optimization based on exergy destruction patterns.

Touaibi and Koten [5] conducted a thermodynamic analysis comparing R1234yf and R1234ze to HFCs in VCR systems. R1234ze exhibited comparable performance to R134a, while also offering substantial reductions in environmental impact, making it a viable low-GWP replacement.

Tarish et al. [6] evaluated subcooling impacts on R1234yf and R1234ze. While R1234yf showed the highest COP enhancement (16.7%), R1234ze exhibited greater total exergy destruction. This indicated trade-offs between performance and irreversibility across refrigerants.

Mclinden and Huber [7] offered a historical perspective on refrigerant evolution, emphasizing the cyclic nature of innovation in the field. Their work elucidated how refrigerant selection is driven by a blend of environmental constraints and technological feasibility.

Ghanbarpour et al. [8] analyzed heat pumps operating with low-GWP refrigerants across four countries. They introduced the concept of a “critical emission factor,” demonstrating how geographical and grid-based factors influence refrigerant sustainability assessments.

Farooq et al. [9] compared various HFOs for commercial air-conditioning systems. R1234ze(Z) stood out for its thermodynamic robustness, but like other HFOs, still required trade-offs in terms of refrigeration capacity versus environmental advantage.

Pundkar et al. [10] explored the use of R513A and R450A in mobile air conditioning systems. While R513A showed reduced COP, R450A improved system performance, highlighting the nuanced performance profiles of HFO-HFC blends.

Alsouda et al. [11] provided a broad overview of natural refrigerants and VCR cycle improvements. Among subcooling methods, suction line heat exchangers and dedicated mechanical subcooling were recognized as highly effective strategies for COP enhancement.

Triki et al. [12] studied a solar-powered VCR system using R1234ze(E) and R134a. R1234ze(E) significantly improved exergy efficiency in all major system components, demonstrating the compound benefit of combining low-GWP refrigerants with renewable energy inputs.

Yi et al. [13] used computational fluid dynamics (CFD) to evaluate centrifugal compressors. R1234ze(E) was identified as a better drop-in replacement than R1234yf due to its smaller COP reduction and better energy efficiency.

Gil and Kasperski [14] investigated ejector refrigeration systems with HFOs and HCFOs. R1243zf and R1234ze(E) delivered the highest COP values in low-temperature scenarios, making them suitable for ejector-based configurations.

Bell et al. [15] compiled data and modeling gaps for refrigerant mixtures. Their findings underscored the limited experimental data on blends involving halogenated olefins, advocating for more extensive property characterization for reliable thermodynamic modeling.

Odunfa and Oseni [16] analyzed nanoparticle-enhanced refrigerants. CuO nanoparticles yielded a 51.1% increase in COP, illustrating the potential of nanofluids in improving heat transfer and compressor efficiency.

Faraldo et al. [17] introduced a hydro-CO2 piston technology, achieving COP improvements up to 56% for refrigeration and 21% for heating. This innovative cycle, integrating subcooling recovery, offers promising avenues for future commercial systems.

Sumeru et al. [18] reviewed subcooling strategies, identifying condensate-assisted subcooling (CAS) as the most effective method with up to 28.9% COP enhancement. Their analysis supports the development of hybrid subcooling systems for R&A applications.

Aprea et al. [19] assessed R1234ze in a domestic refrigerator, reporting 8% lower annual energy consumption and significantly reduced TEWI and LCCP values. These findings support near drop-in substitution of R134a with HFO alternatives.

Gupta et al. [20] offered a comparative thermodynamic analysis of fourth-generation refrigerants. HFOs exhibited lower GWP but required higher power input, reflecting a performance-environment trade-off that must be carefully managed.

Mishra and Khan [21] performed an exergy analysis of a system using R1234yf and R1234ze. R1234ze showed comparable performance to R134a, while R1234yf offered advantages under higher evaporator temperature conditions.

Fedele et al. [22] updated the thermophysical property database for low-GWP refrigerants. While R1234yf and R1234ze(E) were well-characterized, significant gaps remain in data for newer compounds like R1336mzz(E), affecting model fidelity.

Allen et al. [23] developed an open-source Python tool for VCR thermodynamic simulation. Their approach integrates CoolProp and offers adaptability for evaluating various refrigerants under user-defined conditions, enabling reproducible system analysis.

Mota-Babiloni et al. [24] reviewed investigations into R1234ze(E), finding it suitable for new system designs with minor modifications. Blends involving R1234ze(E) showed promise but still faced GWP-related limitations for long-term use.

Mclinden et al. [25] highlighted the difficulty in identifying an ideal refrigerant due to conflicting requirements across GWP, efficiency, and flammability. They emphasized system-level innovation to accommodate future refrigerants.

Mogaji et al. [26] demonstrated the use of a dedicated mechanical subcooling cycle in a two-stage IVCR system. Their findings confirmed COP improvements of up to 33.5% and faster cooling rates, with practical applications in tropical climates.

Olaoke et al. [27] proposed a polynomial regression model for refrigerant property calculation, reducing computation time significantly without loss of accuracy. This innovation is crucial for real-time control and embedded system integration in HVACR.

III. ANALYSIS & DISCUSSION

A comprehensive examination of the 27 referenced studies reveals critical insights into the performance, environmental sustainability, and integration challenges of low-GWP refrigerants—primarily hydrofluoroolefins (HFOs)—and the role of subcooling techniques in optimizing vapor compression refrigeration systems (VCRS).

A. Performance Trade-Offs in Low-GWP Refrigerants

A recurring theme across the literature is the performance compromise involved in adopting low-GWP alternatives. Refrigerants like R1234ze(E) consistently exhibit favorable coefficients of performance (COP) when compared with R134a, especially under optimized conditions, as demonstrated by Belman-Flores et al. [1], Agarwal et al. [4], and Yi et al. [13]. However, studies such as Farooq et al. [9] and Gupta et al. [20] note reductions in cooling capacity and increased compressor work for certain applications, necessitating system-level redesigns to fully realize performance gains.

Furthermore, refrigerant blends (e.g., R513A, R450A) offer a balance between thermodynamic performance and environmental compliance, as seen in the work of Prasad et al. [3] and Pundkar et al. [10]. These blends exhibit moderate efficiency enhancements while allowing partial compatibility with existing systems.

B. Environmental and Lifecycle Impact

Nearly all reviewed works affirm the environmental advantage of HFOs, primarily due to their ultra-low GWP and zero ozone depletion potential (ODP). Studies using TEWI and LCCP metrics (e.g., Aprea et al. [19], Ghanbarpour et al. [8], and Triki et al. [12]) emphasize the need to consider both direct emissions and indirect emissions from electricity use. Notably, Ghanbarpour et al. [8] introduces the concept of a critical emission factor, suggesting that refrigerant selection must be context-specific based on regional power grid characteristics.

The lifecycle assessments clearly indicate that refrigerants such as R1234ze(E) and R1234yf can offer substantial reductions in climate impact without drastically compromising energy efficiency.

C. Subcooling Techniques and System Enhancements

Dedicated mechanical subcooling (DMS), condensate-assisted subcooling (CAS), and nanoparticle enhancement are the most researched subcooling techniques. Solanki et al. [2] and Mogaji et al. [26] demonstrated COP improvements up to 33%, while Sumeru et al. [18] highlighted CAS as a simple yet highly effective approach.

Subcooling was also found to reduce irreversibilities in key system components, notably in studies like Agarwal et al. [4] and Tarish et al. [6]. These enhancements not only improve energy efficiency but also reduce compressor work, thereby prolonging component life and reducing operational costs.

D. Thermophysical Data and Simulation Advances

Accurate modeling remains a cornerstone for refrigerant evaluation. Bell et al. [15] and Fedele et al. [22] underscore the importance of filling data gaps, particularly in thermodynamic properties and transport behavior of HFOs. Meanwhile, simulation tools such as Python-based thermodynamic solvers (Allen et al. [23]) and advanced regression models (Olaoke et al. [27]) are emerging to accelerate analysis and facilitate system-level optimization.

Such tools bridge experimental and computational studies, offering scalable and reproducible platforms for virtual testing across varying system configurations and refrigerant conditions.

E. Challenges in Transition and Implementation

While several HFOs perform comparably or better than HFCs, practical deployment remains challenging. Mclinden et al. [25] and Mota-Babiloni et al. [24] argue that the "ideal refrigerant" is elusive due to trade-offs in flammability, toxicity, thermodynamic compatibility, and cost.

Moreover, as noted by Gil and Kasperski [14] and Faraldo et al. [17], system configurations such as ejector cycles and hydro-CO2 piston systems require advanced engineering control, which may limit immediate adoption but show promise for long-term sustainability.

IV. CONCLUSIONS

The transition toward sustainable and efficient refrigeration systems is gaining momentum through the dual pathways of adopting low-GWP refrigerants—especially hydrofluoroolefins (HFOs)—and integrating subcooling techniques within vapor compression refrigeration systems. This comprehensive review of 27 peer-reviewed studies confirms that refrigerants such as R1234ze(E), R1234yf, and blends like R513A and R450A can function as effective drop-in or modified replacements for R134a, with measurable improvements in energy efficiency and significant reductions in environmental impact.

Subcooling strategies, notably dedicated mechanical subcooling (DMS), condensate-assisted subcooling (CAS), and nanoparticle-enhanced systems, were consistently shown to elevate system performance and reduce irreversibilities. While the performance of some HFOs lags marginally behind traditional refrigerants in terms of cooling capacity or COP, their ultra-low GWP values and compatibility with existing infrastructure make them strong candidates for large-scale deployment.

However, widespread adoption of low-GWP refrigerants and advanced subcooling techniques requires overcoming challenges such as limited thermophysical data, flammability classifications, system design complexities, and region-specific grid emission factors. As simulation tools and experimental datasets mature, future VCR system development will increasingly rely on integrated optimization frameworks that consider environmental, thermodynamic, and economic parameters concurrently.

This review affirms the critical role of HFO refrigerants and subcooling strategies in shaping the next generation of refrigeration systems aligned with global climate commitments.

V. ACKNOWLEDGMENT

The author expresses deep gratitude to Dr. B.K. Chourasia, Professor and Head, Department of Mechanical Engineering, *Jabalpur Engineering College, Jabalpur*, for his insightful guidance, constant encouragement, and invaluable mentorship throughout this research endeavor. His expertise and commitment to academic excellence have been instrumental in shaping the direction and depth of this review work.

Sincere thanks are also extended to *Jabalpur Engineering College* for providing the academic environment and resources necessary for the successful completion of this study.

The author gratefully acknowledges the contributions of the numerous researchers and authors whose published works formed the backbone of this comprehensive literature review. Their dedication to advancing knowledge in the fields of low-GWP refrigerants and subcooling techniques has significantly enriched this paper.

A heartfelt appreciation is reserved for the author's parents, whose unwavering support, sacrifices, and encouragement have been a constant source of strength and inspiration.

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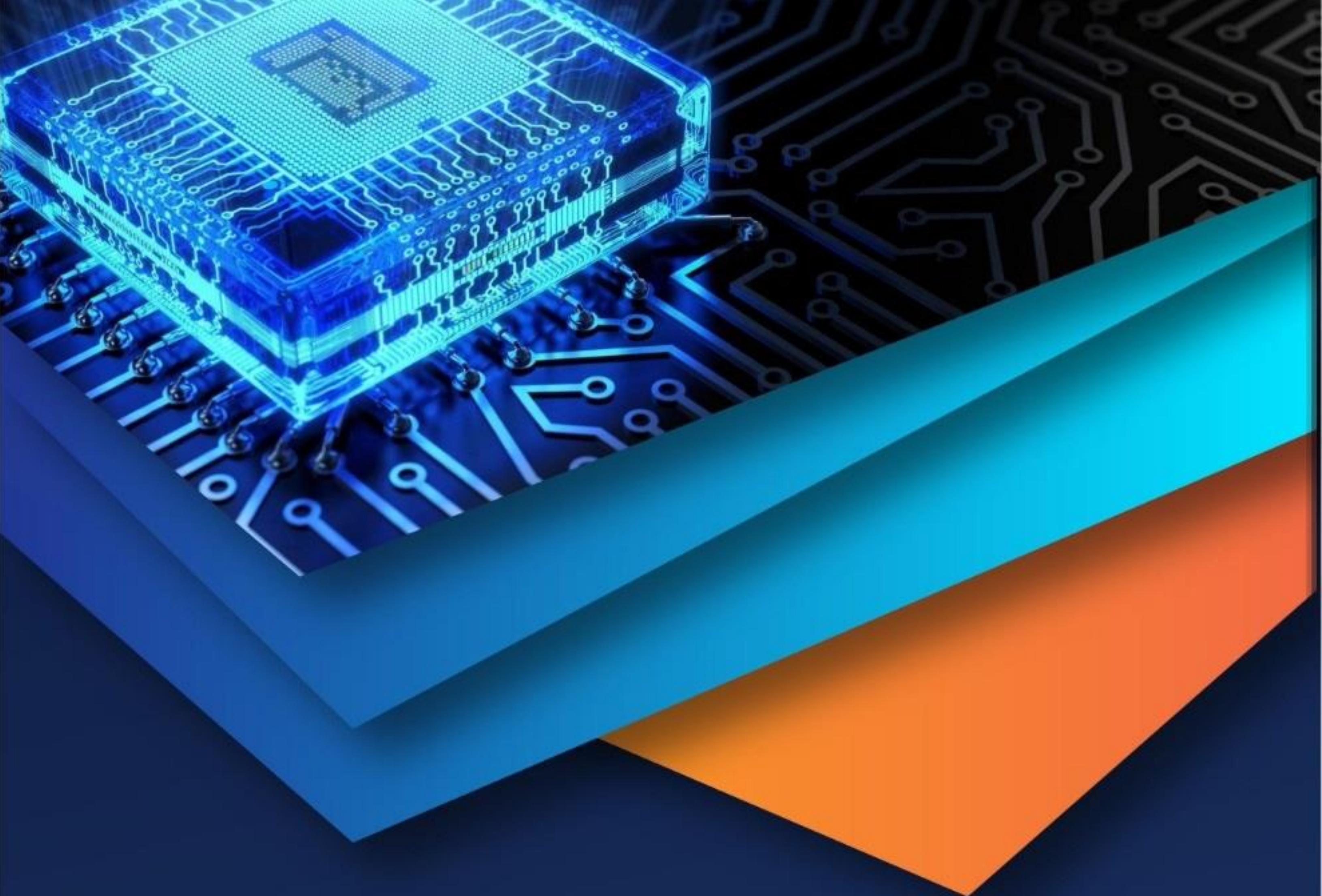

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