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Performance Analysis of Vapour Compression Refrigeration Systems with Refrigerant R32– A Review

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Abstract

As the world moves away from refrigerants that harm the climate, a mildly flammable alternative called R32 is quickly becoming the new standard for modern cooling systems. This analysis compares R32 to traditional options like R410A, R134a, R22, and R290 to see how well it performs. The results are impressive. R32 offers up to 37% more cooling power than older refrigerants and transfers heat much more effectively. Because of this, engineers can design much smaller cooling systems that require significantly less refrigerant to do the exact same job.

However, there is a notable downside, R32 causes the system's compressor to run excessively hot, which leads to wasted energy and mechanical strain. To fix this overheating issue, engineers use advanced design tweaks. Features like flash chambers and multi-evaporator setups work very well to prevent energy loss. On the other hand, using heat exchangers requires extremely precise tuning, or they can actually make the overheating worse. Despite these challenges, R32 remains a highly practical and energy-efficient choice. While the systems require specialized oils to run smoothly, clever engineering can boost performance even further. For instance, by adding custom-designed ejectors, the system can capture and recycle energy that is normally lost during the cooling process, making R32 an incredibly powerful and efficient solution.

Keywords
Refrigerant R32, Vapour Compression Refrigeration System (VCRS), Exergy Destruction, Global Warming Potential (GWP), Flash Chamber, Coefficient of Performance (COP), Nanolubricants.

Nomenclature

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers **COP** Coefficient of Performance

EER Energy Efficiency Ratio

GWP Global Warming Potential

HFC Hydrofluorocarbon

LVHX Liquid-Vapor Heat Exchanger

ODP Ozone Depletion Potential

PAG Polyalkylene Glycol
POE Polyolester

TEWI Total Equivalent Warming Impact

VCRS Vapour Compression Refrigeration System **R22**

Chlorodifluoromethane

R32 Difluoromethane

R134a 1,1,1,2-Tetrafluoroethane

R290 Propane

R410A Zeotropic blend of R32 and R125 **R717** Ammonia

SiO2 Silicon Dioxide

TiO2 Titanium Dioxide

1. Introduction

The global refrigeration and air conditioning sector is currently undergoing a critical transition driven by international climate agreements, including the Kigali Amendment to the Montreal Protocol, which mandate the phase-out of high-GWP refrigerants[1,2]. R410A and R134a, long the standard for residential and commercial applications, face imminent phase-down; R410A specifically is targeted due to its high GWP of approximately 2088[2]. Consequently, R32 (difluoromethane) has emerged as a primary transitional and long-term alternative.[1] Classified by ASHRAE as an A2L (mildly flammable) single-component refrigerant, R32 balances environmental compliance with robust technical feasibility, requiring specific safety considerations in system design and charge limits.[3] Integrating R32 into standard VCRS architectures presents unique thermodynamic and operational challenges—most notably elevated compressor discharge temperatures—yet R32 possesses highly favorable thermophysical properties that reduce overall environmental impact[1,4] Thermophysically, R32 features a high critical temperature, high vapor density, and a high latent heat of vaporization that drives superior heat transfer coefficients—averaging 20% to 40% higher than R22. These properties allow for a much lower mass flow rate, enabling systems to require 20% to 30% less refrigerant by mass while facilitating more compact equipment sizing. Energetically, R32 consistently outperforms legacy baselines, delivering an 11% higher capacity than R410A under standard rated conditions, a 30% to 37% higher volumetric cooling capacity than R22 and R134a, and an approximately 87% higher cooling capacity per unit volume than R290 (propane)[5].However, fully exploiting R32's capacity introduces significant exergetic and operational hurdles. The compressor acts as the primary site of exergy destruction, where R32's inherently high specific heat ratio generates extreme thermal gradients and elevated entropy generation compared to hydrocarbon alternatives. This results in compressor discharge temperatures that range 10°C to 25°C higher than R410A, peaking between 130°C and 150°C under demanding loads. Such extreme heat degrades traditional mineral oils, necessitating highly miscible synthetic alternatives like Polyolester or Polyalkylene Glycol to prevent mechanical failure; these inherent irreversibilities demand advanced cycle modifications.[6,7,8] Integrating multi-evaporator architectures, flash chambers, and work recovery devices—such as custom-designed ejectors to recover lost expansion work—is critical to mitigating thermal stress and maximizing the exergetic efficiency of R32 systems.[9,10]

This review paper evaluates the thermodynamic, energetic, and environmental performance of R32 as a low-GWP alternative to legacy refrigerants (R410A, R22, R134a, R290) in Vapour Compression Refrigeration Systems (VCRS). Specifically, it synthesizes R32's thermophysical advantages—such as enhanced cooling capacity and reduced charge requirements—against key operational hurdles, including high compressor discharge temperatures, lubricant degradation, severe exergy destruction, and A2L flammability constraints.

Furthermore, it assesses cycle optimizations (flash chambers, ejectors, nanolubricants, multi-evaporator systems) while highlighting
critical research gaps: the lack of physical experimental validation for complex multi-stage architectures, dynamic off-design instability in ejectors, long-term nanolubricant stability risks, and unrefined frameworks to balance suction superheat trade-offs.

2. Thermophysical and Environmental Characteristics

The transition to R32 is underpinned by its highly favorable balance of environmental and thermophysical metrics. Environmentally, R32 features a zero Ozone Depletion Potential (ODP) and a GWP of approximately 675, representing a roughly 67% reduction compared to R410A and ensuring compliance with global phase-down regulations[1]. Beyond direct emission metrics, the Total Equivalent Warming Impact (TEWI) for R32 systems has been shown to be up to 18% lower than comparable R410A systems, primarily due to higher energy efficiency reducing indirect electrical emissions[2]. R32 has a boiling point of -51.7°C, a freezing point of -136°C, and a critical temperature of 78.1°C.

Thermophysically, R32 is characterized by a notably high critical temperature, high vapor density, and high latent heat of vaporization, driving superior heat transfer coefficients[11]. Research on two-phase flow and boiling heat transfer indicates that R32 yields an average heat transfer coefficient 20% to 40% higher than that of R22[12]. From an engineering perspective, this high latent heat allows for a much lower mass flow rate to achieve the desired refrigerating effect. These properties facilitate greater heat exchange rates per unit mass, allowing for reduced equipment sizing, more compact and material-efficient architectures, and lower overall system charge requirements, which is critical for managing its A2L flammability limits[3].

3. Comparative Energetic Performance Analysis

First-law thermodynamic evaluations demonstrate that R32 consistently provides superior cooling capacity compared to legacy hydrofluorocarbons and hydrocarbons[4,13].

1. **Comparison with R410A:** Under standard Air-Conditioning and Refrigeration Institute rated conditions, theoretical models indicate that R32 delivers an 11% higher capacity and a 3% higher efficiency than R410A[8]. In commercial and residential air conditioning applications, R32 systems achieve
energy efficiency ratio (EER) improvements ranging from 3% to 15% while maintaining excellent system efficacy.[1,14]

2. **Comparison with Legacy Baselines (R22, R134a, Hydrocarbons):** Analytical models demonstrate that R32 yields a substantially higher volumetric capacity than older HFCs and hydrocarbons.[13] Specifically, it delivers a 30% to 37% higher volumetric cooling capacity than baselines like R22 and R134a, enabling highly compact compressor designs.[5,11] When compared to R290 (propane), R32 yields an approximately 87% higher cooling capacity per unit volume[4,13], though its theoretical COP can be marginally lower (approximately 3.7%) due to increased compression work requirements depending on the exact cycle configuration. Optimized modern R32 systems achieve electricity consumption reductions of up to 10% compared to R22[11]

3. **Charge Reduction:** Because of its high density and enhanced heat transfer coefficient, the optimum refrigerant charge for an R32 residential system is typically 70% of the required R410A amount, and has been recorded as low as 30.4% in specific retrofitted household units[2,14]. Generally, systems require 20-30% less refrigerant by mass to achieve the same cooling effect as an R410A system.

4. Exergetic Performance and Irreversibility

While energetic analysis provides insight into capacity, second-law exergy analysis is critical for pinpointing system inefficiencies and quantifying entropy generation. In standard VCRS architectures, the compressor consistently acts as the primary site of exergy destruction and irreversibility for R32[6]. The inherently high specific heat ratio of the refrigerant generates extreme thermal gradients during compression[6]. This high thermal gradient directly increases entropy generation, leading to heightened system irreversibility when compared to hydrocarbon alternatives like R290[6,13]. Accurate prediction of these irreversibilities across varying operating temperatures often relies on robust thermodynamic modeling utilizing engineering equation solvers.

To achieve true optimization, energetic capacity must be balanced against this exergetic efficiency. Simple

modifications introduce thermodynamic trade-offs. For instance, integrating a Liquid-Vapor Heat Exchanger (LVHX) successfully increases cooling capacity via liquid subcooling; however, the resulting suction gas superheat exacerbates R32's already high discharge temperatures. This inadvertently increases compressor irreversibility unless the LVHX effectiveness is strictly optimized through rigorous mathematical modeling[15].

5. Advanced Cycle Modifications and Optimizations

To fully exploit R32's volumetric capacity while mitigating its inherent irreversibility and extreme discharge temperatures, engineers deploy advanced structural modifications[9,16]:

1. **Multi-Evaporator Architectures:** Complex multi-evaporator VCRS configurations are prioritized for optimizing R32's operational efficiency[9,10]. These advanced structural configurations can accommodate different cooling loads simultaneously and offer the most promising pathway to fully unlocking R32's energetic potential. Developing robust mathematical models and thermodynamic simulations for these frameworks is critical for mitigating inherent exergy destruction across multiple evaporators and expansion stages[6,9].
2. **Flash Chamber Integration:** Implementing multi-pressure, two-stage compression cycles equipped with flash chambers is highly effective[9,10]. By separating flash gas before it reaches the evaporator and cooling the intermediate vapor between stages, inter-stage compression losses are drastically reduced[9]. This specific modification maximizes the COP while actively minimizing total system exergy destruction, ultimately making the cycle thermodynamically tighter.[6,9]
3. **Vapor and Liquid Injection:** Injecting fluid directly into the compressor actively suppresses peak discharge temperatures. Numerical simulations indicate that two-phase injection significantly outperforms standard liquid injection, providing a COP improvement of 4.8% and a cooling capacity increase of 11.8%. Vapor injection heat pump systems using R32 have also demonstrated COP improvements of 1.2% to 5.7% over non-injected cycles.[16]
4. **Work Recovery Devices:** Utilizing ejectors or expanders in place of standard isenthalpic expansion valves recovers kinetic energy. Given R32's high pressure ratios (roughly 7% higher than R290), recovering this work directly reduces primary throttling irreversibility.[13]
5. **Ejector:** Integrating an ejector into a Vapor Compression Refrigeration System (VCRS) using the low-GWP refrigerant R32 significantly enhances thermodynamic performance by recovering expansion work typically lost during standard throttling [17]. This modification effectively pre-compresses the suction gas, reducing the primary compressor's workload and leading to notable improvements in both the energetic Coefficient of Performance (COP) and overall exergetic efficiency [18]. While advanced setups like two-stage suction ejectors offer even greater theoretical cooling capacities [19], translating these theoretical gains into practical efficiency requires carefully managing system operating conditions [20] and rigorously optimizing the ejector's internal geometry to specifically match R32's unique thermophysical properties [21].
6. **Nanolubricants:** To further combat extreme thermal stress, recent tribological research highlights the efficacy of nanolubricants—dispersing nanoparticles such as Silicon Dioxide (SiO_2) and Titanium Dioxide (TiO_2) into the base oil. This significantly enhances thermal stability and heat transfer, effectively reducing compressor friction and wear while simultaneously improving overall energy performance.[7]

6. Operational and Safety Challenges

The primary technical hurdle for R32 adoption is its elevated compressor discharge temperature, which threatens the mechanical and chemical integrity of the system[2,8]. These temperatures typically range 10°C to 25°C (12 to 21 K) higher than R410A, and under demanding operational conditions, can spike between 130°C and 150°C[1,8].

1. **Lubricant Degradation:** These extreme thermal gradients can lead to the failure of traditional mineral oils, resulting in inadequate oil return, increased friction, and eventual mechanical failure. Reliable operation necessitates highly miscible synthetic lubricants, such as Polyolester (POE) or Polyalkylene Glycol (PAG)[2,8]. Pairing R32 with POE oil has been shown to yield a 14% performance improvement over baseline

R410A systems.[8]

2. **Flammability:**As an A2L fluid, R32 requires rigorous safety compliance regarding maximum allowable charge limits, leak detection, and ventilation protocols, which can restrict its use in massive, single-circuit applications without advanced safety measures.[3] Its 2L classification rests on measurable combustion properties, chiefly flammability limits and laminar burning velocity. An updated detailed kinetic mechanism, built on the NIST HFC mechanism and validated against spherical-chamber experiments, can now predict R32/air burning velocity and adiabatic flame temperature reliably. It also shows that a higher fluorine fraction, F/(F+H), lowers flame temperature and speed. Such models give industry and regulators a computationally efficient way to assess the flammability of R32 and its blends, supporting evidence-based charge limits and safer HVAC system design.[22]

7. Industrial and Specialty Applications

R32's high volumetric capacity translates well beyond residential systems. In heavy industrial refrigeration, it serves as a highly viable alternative to ammonia (R717). R32 offers a volumetric capacity approximately 60% higher than ammonia, permitting significant reductions in compressor swept volume and overall equipment footprint.[10] Additionally, R32 has demonstrated robust exergy efficiency and stable COP in specialty maritime fishing vessel refrigeration and industrial ice plant test rigs[23].

8. Limitations and Research gaps

1. **Compressor Irreversibility:** R32's high specific heat ratio causes severe exergy destruction and steep thermal gradients, generating greater entropy than hydrocarbon alternatives.
2. **Extreme Discharge Temperatures:** Operating up to 25°C hotter than R410A (peaking at 150°C), R32 degrades standard mineral oils, necessitating synthetic POE or PAG lubricants.
3. **Nanolubricant Stability:** Despite the thermal benefits of SiO2 and TiO2 additives, long-term risks like nanoparticle agglomeration, sedimentation, and phase-change chemical interactions remain under-researched.
4. **LVHX Trade-Offs:** While internal subcooling boosts capacity, it superheats suction gas and worsens compressor temperatures. Frameworks to balance these exergetic penalties are underdeveloped.
5. **Ejector Optimization:** Practical work recovery is hindered by off-design instability and a lack of empirical data on internal geometries calibrated specifically for R32's dynamics.
6. **A2L Flammability Constraints:** Strict charge limits restrict scalability in large commercial equipment, requiring validated chemical kinetic models for safe expansion.
7. **Multi-Stage Empirical Validation:** Research relies heavily on idealized simulations; physical experimental validation for dynamic loads and inter-stage control in complex architectures remains scarce.

Conclusion

Refrigerant R32 is a high-performance, environmentally friendly replacement to traditional HFCs, with improved volumetric cooling capacity and favorable heat transfer qualities that enable more compact and material-efficient system designs. While its low GWP compared to traditional options like R410A, R134a, R22, and R290, is consistent with stringent environmental protocols, its implementation necessitates overcoming significant thermodynamic and operational challenges, including elevated compressor discharge temperatures, the need for synthetic or nano-enhanced lubricants, and inherently high system irreversibility concentrated in the compressor which can be mitigated by various modifications like flash chamber integration, ejector usage, vapour and liquid injection, etc.

The standard single-stage cycle evaluations of R32 are already extensively documented. Future optimization efforts must prioritize complicated designs in order to address these exergetic consequences. The thermodynamic modeling, mathematical formulation, and experimental validation of multi-evaporator VCRS frameworks that use flash chambers is a significant frontier.These multi-stage arrangements provide the most viable avenue to fully utilizing R32's energetic potential while systematically minimizing its key sources of exergy destruction.

The overall performance of R32 refrigerant compared to the other traditional low-GWP alternatives was

studied where R32 was found to have multiple advantages such as higher cooling capacity and reduced charge requirements. The optimization of a VCRS cycle running on R32 was also studied using different modifications(Flash chamber, ejectors, nanolubricants, multi-evaporator systems). Research Gaps were found in lack of physical experimentation validation of complex architectures , long-term nanolubricant stability risks, unrefined frameworks for balance.

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