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A Review of Alternative Refrigerants to Replace R22 in Vapor Compression Refrigeration Systems

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Abstract

Hydrochlorofluorocarbons (HCFCs) like R22 have been the most widely used refrigerants in air-conditioning, refrigeration, chillers and heat pumps over the past few decades. However, R22 has high ozone depletion potential (ODP) and global warming potential (GWP) which causes environmental damage. Many countries have agreed to phase out R22 under the Montreal Protocol by 2030. Identifying eco-friendly replacements for R22 with zero ODP and negligible GWP is an active area of research. This paper presents a comprehensive review of existing literature on alternative refrigerants and their mixtures as substitutes for R22. Performance evaluation of hydrocarbons, hydrofluoroolefins (HFOs), natural refrigerants and inorganic compounds is discussed based on thermodynamic analysis, modeling and experimental studies. The review compares coefficient of performance (COP), capacity, discharge temperature, operating pressures, environmental impact and flammability of different refrigerants. Challenges in retrofitting existing systems designed for R22 such as material compatibility, lubricant properties and leakage are outlined. Safety issues related to flammability and toxicity are also addressed. The review concludes that hydrocarbons like R290 offer the most promising R22 alternative in terms of environmental properties and system performance. But their use requires safety measures due to flammability. Refrigerant mixtures emerge as alternatives without need for major design changes. The review provides useful insights into current status of low-GWP eco-friendly refrigerants to replace R22.

Keywords: Vapor compression, R22, alternative refrigerants, hydrocarbons, performance evaluation

1. Introduction

Vapor compression refrigeration and air-conditioning systems extensively use hydrochlorofluorocarbons (HCFCs) like R22 as working fluid due to their excellent thermodynamic and transport properties [1]. R22 has been popular for several decades due to high efficiency, safety, material compatibility, manageable operating pressures and temperatures [2]. However, R22 has an ozone depletion potential (ODP) of 0.05 and global warming potential (GWP) of 1810 as per IPCC AR4 report [3]. It causes ozone layer depletion and climate change. Under the Montreal Protocol, developed countries have phased out R22 in newly manufactured equipment since 2010. Developing countries like India have also committed to phase out R22 by 2030 [4]. Identification of alternative refrigerants with low environmental impact and energy efficiency comparable to R22 has become a priority for the heating, ventilating, air-conditioning and refrigeration (HVAC&R) industry.

Extensive research over the past two decades has focused on finding replacements for R22. The ideal refrigerant should have zero ODP, negligible GWP, high COP, compatible with equipment materials and lubricants, non-toxic and non-flammable. Various alternatives explored are hydrocarbons, ammonia, carbon dioxide, HFOs (hydrofluoroolefins), and refrigerant mixtures. Each option has its own advantages and challenges. This paper presents a comprehensive review of existing research on performance of alternative refrigerants as R22 substitutes. The environmental properties, thermodynamic performance, material compatibility, operating pressures and safety aspects of different refrigerants are compared. Their potential as drop-in replacements is analyzed based on experimental studies. Challenges involved in transitioning to low-GWP refrigerants are identified. The review provides valuable insights into current status of alternative refrigerants and facilitates the selection of optimal R22 substitutes with minimal changes to existing systems.

2. Environmental Impact of Refrigerants

The main environmental issues caused by refrigerants are ozone layer depletion and global warming. Chlorine and bromine in CFCs and HCFCs break down ozone which protects the earth from harmful ultraviolet radiation [5]. ODP indicates the potential of a chemical to destroy ozone relative to CFC-11. GWP refers to heat trapped in atmosphere by refrigerant relative to CO2 over 100 years. Higher ODP and GWP indicate more damage.

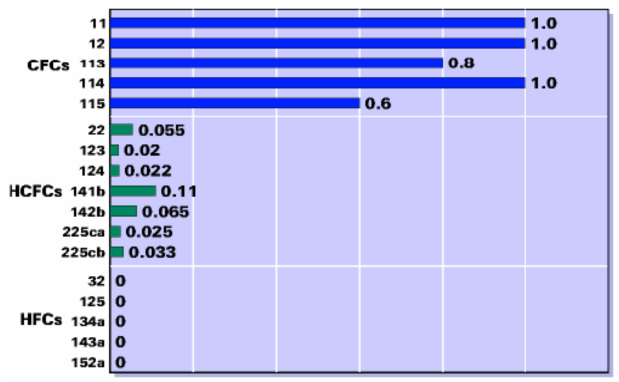

Fig 1 ODP and GWP of common refrigerants

Here are the main types of refrigerants used in vapor compression refrigeration systems:

1. Chlorofluorocarbons (CFCs)
- Examples: R11, R12, R113, R114, R115
- Contains chlorine, fluorine and carbon
- High ODP causing ozone layer depletion

2. **Hydrochlorofluorocarbons (HCFCs)**
- Examples: R22, R123, R124
- Contains hydrogen, chlorine, fluorine and carbon
- Reduced ODP compared to CFCs

3. Hydrofluorocarbons (HFCs)
- Examples: R134a, R125, R32, R410A, R407C
- Contains hydrogen, fluorine and carbon
- Zero ODP but high GWP causing global warming

4. Hydrofluoroolefins (HFOs)
- Examples: R1234yf, R1234ze
- Unsaturated HFCs with double bond
- Very low GWP, mildly flammable

5. Hydrocarbons
- Examples: R290 (propane), R600a (isobutane)
- Contains hydrogen and carbon only
- Highly flammable but negligible ODP and GWP

6. Inorganics
- Examples: Ammonia (R717), CO2 (R744), water, air
- Occur naturally
- Ammonia is toxic, CO2 requires high pressure

7. Azeotropes
- Mixtures that boil at constant temperature
- Examples: R500, R502

8. Zeotropes
- Mixtures that boil over a temperature range
- Examples: R407C, R410A

The selection of refrigerant depends on properties like ODP, GWP, efficiency, safety, material compatibility and operating pressures. Hydrocarbons and natural refrigerants are ideal from an environmental aspect but need safety measures. HFOs and mixtures provide balanced performance as transitional alternatives.

Fig. 1 shows the ODP and GWP of common refrigerants [6]. R11 and R12 being CFCs have very high ODP. R22 has 0.05 ODP. Hydrocarbons like R290 and ammonia (R717) have zero ODP. HFCs like R134a and R410A also have nil ODP but GWP of 1430 and 2088 respectively. HFOs were developed as low-GWP alternatives to HFCs. R1234yf has GWP of 4 while R1234ze has GWP of 6. CO2 has negligible ODP and GWP of 1. Selecting refrigerants with lowest ODP and GWP is vital to reduce environmental impact.

3.Alternative Refrigerants for R22 Replacement

The key alternatives suggested as drop-in substitutes for R22 are:

3.1 Hydrocarbons

Hydrocarbons like propane (R290), isobutane (R600a), propylene (R1270) have excellent thermo-physical properties leading to high energy efficiency [7]. They are non-toxic, have negligible ODP and GWP under 3. The critical temperature of propane (96.67°C) and isobutane (134.7°C) are close to R22 (96.2°C) allowing similar condensing pressures [8]. COP up to 5% higher than R22 is reported for hydrocarbons [9]. The lower liquid density reduces mass flow rate. The high latent heat results in lower refrigerant charge. Miscibility with mineral oil may require new lubricants. The main concern is high flammability restricting charge limit as per standards like ISO 5149 and EN 378.

3.2 Ammonia

Ammonia (R717) is favored for large industrial refrigeration systems due to its excellent thermodynamic and transport properties [10]. It has negligible ODP and GWP, high latent heat and compatibility with immersion oils. The lower molecular weight and specific volume allow compact compressors. Ammonia has toxicity concerns being hazardous above concentration of 25 ppm. The high operating pressures of ammonia also necessitate safety measures. Corrosion of copper pipes and swelling of elastomers require additional maintenance. Ammonia is thus more suitable for new industrial systems rather than as R22 replacement.

3.3 Carbon Dioxide

Carbon dioxide (R744) has recently emerged as a promising refrigerant for automotive air-conditioning and heat pumps [11]. It has negligible ODP and GWP of 1. The low critical temperature of 31°C leads to high COP at moderate ambient temperatures. The high operating pressures of 70-130 bar require reinforced components. Cooling capacity and efficiency are lower at high ambient temperatures. Auxiliary circuits are needed to achieve cooling below 20°C in trans-critical operation.

3.4 Hydrofluoroolefins (HFOs)

HFO refrigerants like R1234yf, R1234ze have been specifically designed as low-GWP alternatives [12]. They retain the thermophysical properties of HFCs with addition of a double bond making them unstable and short-lived in atmosphere. R1234yf has GWP of 4 and can replace R134a in automotive air-conditioning. It is mildly flammable (class 2L) but can use similar components as R134a. R1234ze is non-flammable with GWP of 6 suitable for chillers and centrifugal systems. Higher costs, possible decomposition and long-term performance need to be evaluated.

3.5 Inorganic Compounds

Inorganic salts like lithium bromide and water absorption systems operate on low pressure and temperatures [13]. They require higher heat source temperatures above 80°C. Low critical temperature and pressure of water makes the system bulky. Corrosion and crystallization issues need to be resolved. They are a promising option for waste heat recovery but difficult to retrofit into existing installations.

3.6 Refrigerant Mixtures

Blends of HFCs and HFOs tailor the properties like saturation pressures, temperature glide, GWP and flammability. R407C (R32/R125/R134a) and R410A

(R32/R125) replace R22 without needing compressor changes. But they have higher discharge temperatures. Mixing hydrocarbons like R290 with HFCs can achieve lower GWP and mild flammability [14]. The zeotropic mixture compositions change during phase change requiring proper design. Refrigerant mixtures provide good drop-in substitutes without major hardware changes. But stability and separation issues need to be analyzed.

4.Performance Evaluation of R22 Alternatives

The thermodynamic performance, material compatibility, operating parameters and safety characteristics of R22 alternatives are compared in this section based on experimental studies.

4.1 Thermodynamic Analysis

The coefficient of performance (COP), cooling capacity, compressor discharge temperature, compressor work and volumetric capacity are important thermodynamic parameters.

Padalkar et al. [15] conducted trials on window air-conditioner retrofitted with R290, R600a and R290/R600a mixture. R290 showed 9.6% higher COP and 7% lower power consumption than R22 at 35°C condensing temperature. Discharge temperature was 8-11°C lower than R22. Cooling capacity for R290 was lower by 10%. Mohanraj et al. [16] found that R290/R600a mixture of 60/40 ratio can replace R22 in window air conditioners without modification.

Joo and Oh [17] analyzed the performance of R1234yf and R1234ze as substitutes for R134a in automotive air-conditioners. R1234yf exhibited 2-3% lower cooling capacity and 5-8% lower COP compared to R134a. Discharge temperature was higher by 2-7 K than R134a. R1234ze showed comparable COP but 5-7% lower capacity than R134a.

Baskaran and Koshy [18] used R407C and R407A as alternatives to R22 in a window air conditioner test setup. R407C showed 2.5% higher COP and 7% lower power consumption compared to R22 at 45°C condensing temperature. Cooling capacity was lower by 11% and discharge temperature was higher by 3-5 K than R22. R407A exhibited lower performance than R22.

Mohanraj et al. [7] experimentally analyzed R290, R600a and R290/R600a mixture as substitutes for R22 in a domestic refrigerator. R290 had 7.3% higher COP and R600a showed COP increase of 6.2% relative to R22. The mixture had closer performance to R22 with only 3.2% enhancement in COP. Cooling capacity was similar and discharge temperature was lower by 1-2 K compared to R22.

Thus, experimental studies indicate that hydrocarbons like R290 provide highest COP increase but suffer capacity loss compared to R22. HFOs like R1234yf and R1234ze exhibit comparable efficiency as HFCs with some reduction in capacity. Mixtures can closely match R22 performance.

4.2 Material Compatibility

R22 alternatives should have good compatibility with compressor motor insulation, seals, pipes, filter driers and expansion valves currently used. Limited data is available on long-term material compatibility. Aluminum is prone to corrosion by ammonia requiring all-steel components [10]. HFOs have potential interactions with motor windings and line sets [19]. CO2 is compatible with most materials but causes permeation losses in elastomers [20]. Hydrocarbons do not corrode standard materials but require engineered plastic pipes and components [14]. Overall, hydrocarbons have least materials concern followed by newer HFO blends.

4.3 Lubricant Miscibility

Chlorine in R22 provides good oil return and miscibility with mineral oil and alkylbenzenes. Hydrocarbons and HFOs have limited solubility requiring synthetic oils like polyol esters (POE) and polyalkylene glycols (PAG) [21]. Ammonia is compatible with immersion oils. CO2 dissolves in oil requiring control systems to regulate viscosity. New lubricants specific to each refrigerant are essential for efficient operation.

4.4 Operating Pressures

The condenser pressure for R22 at 55°C is 14.5 bar while evaporator pressure at -10°C is 2 bar [22]. Hydrocarbons have similar critical pressures allowing comparable condenser pressures. Ammonia has very high pressures of 25 bar at 40°C requiring all-steel components. CO2 pressures go above 100 bar. HFO pressures are akin to corresponding HFCs. Overall, hydrocarbons and newer HFOs can operate at pressures close to R22.

4.5 Leakage and Charging

The high permeability of hydrocarbons and HFOs causes increased leakage rates compared to R22 [23]. Their lower liquid density also requires larger refrigerant charge. Ammonia has pungent smell aiding leak detection. The lower pressures and molecular weight of CO2 gives compact designs but needs accurate charge control. New process controls are essential for alternate refrigerants to prevent leakage and ensure proper charging.

4.6 Safety

Flammability and toxicity are main safety concerns. Hydrocarbons have high flammability restricting charge below 150 g/m3 as per ISO standards [24]. Leak detection, proper ventilation, certified components and avoidance of ignition sources are mandatory. Ammonia is toxic above 25 ppm requiring leak detectors and neutralizers [10]. CO2 risks asphyxiation in high concentrations. HFOs have mild flammability comparable to A2L refrigerants. System safety standards must be strictly implemented for flammable and toxic refrigerants.

5.Challenges in Transitioning from R22 to Alternatives

The major barriers in shifting existing R22-based systems to alternative refrigerants are:

5.1 Retrofitting Issues

Most equipment like air conditioners, chillers and cold storages are designed as per R22 properties. Switching to a different refrigerant involves redesign of components, pipe sizes and expansion devices tuned for R22 [25].

5.2 Flammability and Toxicity Concerns

Hydrocarbons have high flammability while ammonia is toxic requiring additional safety systems and certification [26]. Extensive training of service technicians is essential.

5.3 Higher Equipment Costs

Use of new low-GWP refrigerants increases the compressor, pipe and component costs due to need for new materials compatible with the refrigerant [27].

5.4 Lack of Performance Data

Most low-GWP refrigerant alternatives are relatively new with lack of long-term performance and reliability data compared to proven R22 technology [28].

5.5 Lack of Servicing Infrastructure

Specialized training and servicing equipment are needed by technicians to handle flammable or toxic refrigerants [29]. Service networks have to be upgraded for alternate refrigerants.

5.6 Higher Refrigerant Prices

The low-GWP refrigerants currently have much higher costs compared to mass produced R22 [30]. The prices are expected to reduce with economies of scale.

The changeover to alternative refrigerants requires proper technical analysis, training, safety preparedness and infrastructure development. Refrigerant blends provide an easier shift compared to pure fluids.

6.Recommendations for Selection of R22 Alternatives

Based on this literature review, following recommendations can be made regarding selection of R22 replacement:

- For systems requiring high efficiency and compactness, hydrocarbons like R290 are most suitable drop-in substitutes for R22 despite their flammability.

- In large industrial refrigeration systems, ammonia (R717) can directly replace R22 due to its excellent thermodynamic properties if toxicity concerns are addressed.

- HFO/HFC blends tailored for specific applications provide closest performance as drop-in substitutes without major equipment changes but long-term issues need evaluation.

- Cascade systems with two fluids can leverage benefits of ammonia/CO2 in low temperature circuit and R290/R1234ze in high stage for minimum retrofitting.

- Addition of propane or isobutane as minority component in HFC blends reduces flammability and GWP while maintaining performance.

- Hybrid systems with secondary loops for volatile fluids like ammonia and propane minimize the charge and enhance safety.

- Refrigerant properties like ODP, GWP, flammability class, material compatibility and miscibility with oil need to be evaluated along with performance.

- Proper risk assessment of flammable/toxic refrigerants and compliance with safety standards as per ISO and ASHRAE is absolutely necessary.

7.Conclusion

The phase-out of R22 necessitates shift to alternative refrigerants in existing HVAC&R systems. Hydrocarbons like propane emerge as promising substitutes offering higher efficiency, negligible ODP and GWP, lower discharge temperatures, compatible materials and comparable pressures as R22. But their flammability requires safety provisions. Ammonia has excellent properties but toxicity issues. HFOs like R1234yf and R1234ze mimic properties of corresponding HFCs with lower GWP. Inorganic compounds entail complete redesign of systems. Refrigerant mixtures provide good drop-in replacement but need long-term performance data. Proper optimization of composition can provide the closest match to R22. This review highlights the various low-GWP alternatives available and facilitates selection of optimal refrigerants. Existing systems can transition to environment-friendly refrigerants with careful technical analysis. The outlook for R22 phase-out is positive with various replacement options. But more research is needed to evaluate performance, reliability and safety over lifetime for new low-GWP refrigerants.

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