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Theoretical Performance Evaluation of Sustainable Refrigerants in Marine Engineering Practice

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Abstract*:* *Refrigeration is, and has been an essential component of marine engineering practice for the past several decades, however, with increasing worldwide awareness of the detrimental effects refrigerants can have on the environment, this "niche" area of the marine engineering profession has undergone major regulatory changes. This article lists the regulatory changes with their enforcement and phase-out date for the most commonly used marine refrigerants, proposes suitable environmentally acceptable alternatives detailing their performance evaluation, and describes the most common problems encountered during the conversion process for existing marine HVAC and provision refrigeration installations both in the off-shore sector and on ocean-going vessels based on statistical data and practical real-world examples witnessed by me in my professional practice.*

Keywords: refrigerants, sustainable, marine engineering practice, vessels, decarbonization, ozone depletion, environmental

I. INTRODUCTION

Refrigerants used onboard ocean-goingvessels over the past few decades have served their purpose very well from an engineering viewpoint, i.e. in terms of achieving desirable operating temperatures, pressures, and optimal specific heat values, however,a significant drawback of these refrigerants, which can no longer be ignored is their detrimental effect on the environment, particularly their inherent potential to deplete the ozone layer, and exacerbate"global warming"

There have been severalinitiatives by the international community to mitigate the harmful effects of these refrigerants, a few noteworthy mentions are,the "Vienna Convention for the Protection of the Ozone Layer" of 1985, the "Montreal Protocol" of 1989, which underwent nine changes from 1990 to 2016, the "Kyoto Protocol" of 1992 and the "European Union (EU) F-gas regulation" of 2014. The most effective of the treaties mentioned above hasundoubtedly beenthe "Montreal Protocol", widely considered the inflection point for global climate change regulation. As a direct result of which climate projections indicate, the ozone layer will return to 1980 levels by the years 2050-2070.

Although there are a plethora of refrigerant gases, this white paper will focus exclusively on R22, R134a, R404A, R407C, R410A, R417A, R422D, R427A, and R507 which are themost commonly used gases inpresent-dayMarnie HVAC and refrigerationinstallations, scheduled to be either phased out,(in which case they must be replaced)or, phased down(in which case they can continue to remain in operation as long as it is either economically viable or till phased out if applicable.)

II. METHODOLOGY

Let us examine the core problem, causes, phase-out / phase-down timelines, proposed sustainable alternative refrigerants, their theoretical performance evaluation, and problems encountered during conversion on existing marine HVAC units, based on statistical data I collected in my professional practice.

2.1 Core Problem

A. Depletion of the Ozone Layer

Research has proven that "ozone" in the stratosphere absorbs ultraviolet radiation which is harmful to living organisms. Without ozone, in the atmosphere, the sun's intense ultraviolet (UV) radiation would annihilate life on Earth. The ozone acts as a shield screening part of solar UV-A radiation, most of the UV-B radiation, and all the UV-C radiation. In addition to causing ecological problems, intense UV-B and UV-C radiation can cause severe sunburn and lead to skin cancer in humans. Therefore, the importance of ozone in the stratosphere, commonly called the "Ozone layer" cannot be overemphasized.

In 1976 atmospheric research revealed that the ozone layer was being systematically depleted primarily by manmade gases such as,

- Chlorofluorocarbons (CFCs)
- Hydrochlorofluorocarbons (HCFCs)

These are commonly called ozone-depleting substances (ODS) and are generally used as aerosol propellants, solvents, and refrigerants. ODS is regulated by MARPOL Annex 6 – Regulation 12 for-:

B. Global Warming

To understand global warming, we must first understand the term "greenhouse effect", which occurs when certain gases in the earth's atmosphere trap infrared radiation, this causes the planet to become warmer, like how a "greenhouse" becomes warmer. The phenomena known as "Global warming" is defined as a gradual increase in the overall temperature of the earth's atmosphere and leads to a plethora of problems including but not limited to a rise in sea levels, melting of ice caps and glaciers, flooding of coastal areas, disruption of weather patterns, variation in temperatures, etc. and is generally attributed to the greenhouse effect as mentioned above.

Although the greenhouse effect is a natural process essential for preserving life on earth, in recent years the effect has become stronger owing to increased levels of,

- Carbon dioxide (CO2)
- Chlorofluorocarbons (CFCs)
- Hydrochlorofluorocarbons (HCFCs),
- Saturated Hydrofluorocarbons (HFCs)

and other pollutants in the atmosphere which have contributed to global warming. Figure 1 shows the historical cycle of refrigerants including CFCs and HCFCs mentioned above.

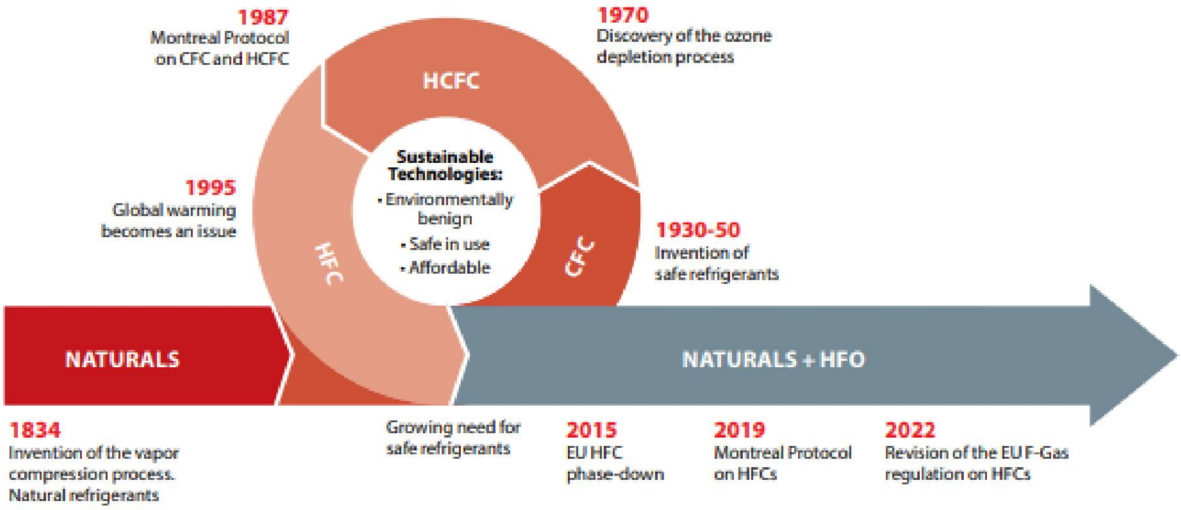

Figure 1 - Historical cycle of refrigerants

2.2 Causes

The potency of an ODS to deplete the ozone layer is measured in terms of a numerical value termed the ozone depletion potential (ODP) which is a quantification of the relative amount of degradation to the ozone layer, it can cause in comparison to trichlorofluoromethane which is assigned an ODP of 1.

Similarly, the measure of the global warming effect of a gas is termed the Global warming potential (GWP). It is defined as the amount of heat trapped by a certain mass of gas relative to the amount of heat trapped by a similar mass of carbon dioxide (CO2) over a specific period.

The following table shows commonly used marine refrigerants with their respective ODP, and GWP values and whether they are to be phased out or phased down by local or international regulations in the future.

F-Gas	Type	ODP	GWP	Phase outor down
R-22	HCFC	.049	1700 (medium)	Phase out
R-134a	HFC	0	1430 (medium)	Phase down
R-404A	HFC	0	3922 (high)	Phase down
R-407C	HFC	0	1774 (medium)	Phase down
R-407F	HFC	0	1824 (medium)	Phase down
R-410A	HFC	0	2088 (medium)	Phase down
R-417A	HFC	0	2346 (medium)	Phase down
R-422D	HFC	0	2729 (high)	Phase down
R-427A	HFC	0	2138 (medium)	Phase down
R-507A	HFC	0	3985 (high)	Phase down

Table1-ODP & GWP values for common marine refrigerants

2.3 Phase out and phase down timelines.

The timeline for phasing out, or phasing down the above refrigerants is determined by the,

- Geographical location and corresponding International or national regulation
- Refrigerant category, whether HCFC or HFC

As different geographical locations are governed by their corresponding regulations, we will discuss the timelines for the two main international regulations which are the "Montreal Protocol" and the "EU-F gas regulation."

A. Montreal Protocol

Following the directives of the Montreal Protocol developed countries have phased out HCFCs by 100% as of January 01, 2020, and developing countries have phased out HCFCs by 35% as of January 01, 2020,which is required to reach 67.5% by January 1, 2025, and finally a 100% by January 01, 2030.

For HFCs, the Montreal Protocol's phase-down schedule is divided into Article 5 and non-article 5 countries, each of which is further subdivided into Group 1 and Group 2. Article 5 countries reduction timeline starts from 2024 ending with an 80% reduction by 2045 for group 1 countries and starts from 2028 ending with an 85%reduction by 2047 for group 2 countries. Non-article 5 countries' reduction ends with an 85% reduction by 2036 for group 1 countries and an 85% reduction by 2036 for group 2 countries.

B. European Union F-Gas Regulation

Per EU regulations No 517/2014, Fluorinated Greenhouse Gases commonly referred to as the EU F-gas regulation, producers and importers are allocated annual quotas of HFCs which are progressively reduced in steps, starting from 2015 to a 79% reduction by 2030.

C. MARPOL Regulation

MARPOL 73, Annex Regulation 12, governs the use of ODS onboard vessels greater than 500 GRT as follows

3.1 Installations that contain ozone-depleting substances other than HCFCs, shall be prohibited:

3.1.1 on ships constructed on or after May 19, 2005: or

3.1.2 in the case of ships constructed before May 10, 2005, which have a contractual delivery date of the equipment to the ship on or after May 19, 2005, or, in the absence of a contractual delivery date, the actual delivery of the equipment to the ship on or after May 19, 2005.

3.2 Installations that contain HCFCs shall be prohibited.

3.2 .1 on ships constructed on or after January 01, 2020: or

3.2.2 in the case of ships constructed before January 01, 2020, which have a contractual delivery date of the equipment to the ship on or after January 01, 2020, or, in the absence of a contractual delivery date, the actual delivery of the equipment to the ship on or after January 01, 2020.

From the above, we see that at present, R-22 has already been phased out in developed countries and as of 2020 production and consumption reduced by 35% in developing countries making it expensive and difficult to procure, primarily due to it being designated as an ODP gas. Similarly, we see HFCs although not phased out, will be progressively phased down primarily due to their GWP, and hence we can reasonably assume they will become more expensive and harder to procure with time. Hence it is advisable to convert HCFC refrigerants like R-22 on existing installations with low GWP HFCs and opt for Hydrofluoroolefins HFOs (Unsaturated Hydrofluorocarbons) and natural refrigerants with low GWP for new installations as far as practically possible as HCFCs are prohibited on ships constructed after January 01,2020, as per MARPOL and HFC's are being phased down.

2.4 Sustainable alternatives

From the previous sections, we are now aware that:

- HCFCs are being phased out worldwide.
- HFCs are being phased down worldwide.

We will therefore investigate the suitability of a sustainable alternative refrigerant to retrofit existing HCFC marine HVAC and reefer installations and install new marine HVAC and reefer installations.

The four main parameters to be considered when looking for an alternative refrigerant are affordability, safety, operational performance, and environmental friendliness. Due to surmounting regulatory pressure to eliminate high GWP refrigerants, it is preferable to consider refrigerants with zero or low GWP values, however, when considering such refrigerants there is unfortunately a tradeoff between low GWP refrigerants and flammability, as can be seen in figure 2 below.

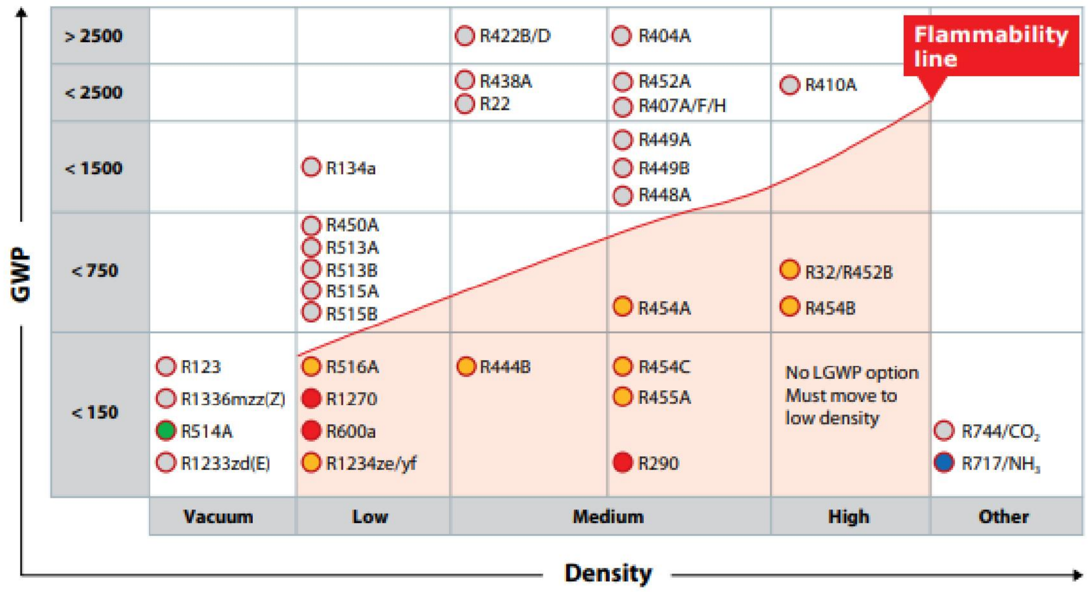

Figure 2- Main refrigerant groups GWP versus density

Legend for Figure 2:

- ● Non-flammable
- ● Mildly flammable
- ● Highly flammable
- ● Toxic non-flammable
- ● Toxic less flammable
- o Presently available
  Not yet easily available

Hence, we find flammability is inextricably linked to GWP and refrigerant capacity.

To reduce the GWP of a refrigerant, it must be made chemically unstable (unsaturated) so that if released into the atmosphere it quickly breaks down and is unable to trap infrared radiation and thereby does not contribute to global warming.

The main group of such unsaturated chemical refrigerants are referred to as "hydrofluorolefins", (HFOs) and classified as "fourth-generation refrigerants". Prominent examples being R1234yf,R1234ze, and R1234zd.

They possess a very low GWP, are mildly flammable, and have a low density (do not require high pressures in the refrigeration cycle). However, despite these advantages, HFOs are generally not considered to be viable marine refrigerants, as,although classified as mildly flammable they are flammable albeit with a low flame propagation speed, have short atmospheric life spans due to their chemical structure, and most importantly, the risks associated in their use concerning human health, safety and the environmental impact of theirde composition products is still not fully established.

Lastly,R744/CO2 and R717/NH3, commonly referred to as "natural refrigerants" (shown as "other refrigerants" in Figure2) may be considered as long-term sustainable alternatives, as they possess low GWP values and are non-flammable, but the tradeoff is they are toxic and therefore require special provisions like detection systems.

Furthermore, R744, due to inherent high working pressures requires compressors that are large enough to achieve the required compression pressures.

Considering the above the alternatives that remain are to:

A) retrofit existing marine HVAC and refrigeration installations with low/medium GWP and medium density HFCs. There remains a good number of years till the final phase down to 79% ~ 85% for HFCs and although the gas procurement cost will go up over time due to supply chain shortages, particularly in the developed world, the cost of converting existing systems to HFC's is still economically the preferred alternative. An additional point of consideration for the retrofit is the choice of a suitable HFC which has a low/medium GWP, and medium density as well as matches the characteristics of the existing refrigerant so that the conversion can be done with the least amount of modification to the plant.

B) ensure marine HVAC and refrigerant systems for newly built vessels and marine structures are designed to use natural refrigerants such as R717 and R714, with adequate risk assessment and safety mitigation measures like the installation of leak detection systems.

2.5 Performance Evaluation

As mentioned in the previous section for retrofitting existing marine HVAC and refrigeration units, depending on the current freon gas that is "in use", the most suitable HFC that has similar thermodynamic characteristics, and thereby does not require extensive modification of machinery and facilitates a low operating cost will be a sustainable alternative.

Considering the above, R407C/F and R134A are at present, sustainable alternatives to retrofit existing R22 and R404A installations which are the most common, marine refrigerants. Retrofitting with a natural refrigerant such as R744 or R717 is not an economically viable alternative, as it requires extensive modification of machinery.

For new vessels R744 and R717 may be considered to be suitable sustainable refrigerants for the future due to low GWP, low operating costs, and global availability, however, they do require additional safety systems like leak detection sensors and robust construction or compression in series to achieve high operation pressures, as in the case of R717

The physical properties of these proposed sustainable refrigerants are seen below in Table 2.

F-Gas	Boiling Point (°C)	Critical Temperature (°C)	Critical Pressure (bar)	Reefer Capacity (kW)
R134A	-26.1	101.1	40	1.22 ~ 8.35
R407C	-43.3	87.3	48	1.35 ~ 9.26
R407F	-46.7	86.2	46	1.34 ~ 9.19
R410A	-48.5	72.8	46	
R717	-33.3	132.4	111	2.67~13.28
R744	-78.5	31.1	73	1.46 ~ 8.36

Table 2- – Physical properties of sustainable marine refrigerants

The refrigerant cycle operating range parameters for sustainable marine refrigerants are seen below in Table 3.

Table 3 - Refrigerant cycle operating range parameters for sustainable marine refrigerants

F-Gas	Evaporator Temperature (°C)	Evaporator Pressure (kPa)	Condenser Temperature (°C)	Condenser Pressure (kPa)	Compressor Temperature (°C)	Compressor Pressure (kPa)
R134A	-30 to -10	350 to 550	30 to 40	1200 to 1400	70 to 100	1100 to 1700
R407C	-35 to -15	300 to 500	30 to 40	1200 to 1400	80 to 120	1000 to 2100
R407F	-30 to -10	350 to 550	30 to 40	1200 to 1400	70 to 100	1100 to 1700
R410A	-35 to -15	350 to 550	30 to 40	1200 to 1400	70 to 120	1100 to 1700
R717	-50 to -25	600 to 900	30 to 40	1200 to 1400	70 to 100	1100 to 1700
R744	-55 to -30	800 to 100	20 to 25	800 to 1000	-20 to 10	800 to 1250

We find from Table 1, Table 2, and Table 3, that R134A, R407C, and R407F have similar physical properties, similar operating range parameters, and lower GWP values compared to HCFC refrigerants like R22 and HFC refrigerants like R404A and R410A which are currently widely “in use” on existing marine offshore structures and ocean-going vessels. R134A, R407C, and R407F can therefore be considered viable alternative sustainable marine refrigerants for conversion on existing HVAC and refrigeration installations, as major system modification is not required.

The choice of whether to retrofit an existing system to R134A, R407C, or R407F will depend on the application, i.e., the capacity of the existing system, the temperatures of the existing system, the refrigerant in use in the existing system, etc. In my practice, I have personally converted numerous existing R22 systems to R407C and existing R404A systems to either R407C or R407F with much success.

For upcoming “new build” marine offshore structures and ocean-goingvessels, R744 and R717 can be considered “future proof”, viable sustainable marine refrigerants due to their “zero” ODP and GWP. However, as stated earlier, theses refrigerants (also known as “natural working fluids”) have safety issues as, R717, is colorless, pungent, mildly flammable, and highly toxic, while R744 is non-flammable but an asphyxiant gas, and hence both refrigerants require additional safety measures like leak detector alarms and well-trained operators. Additionally, R744 has high working pressures and therefore requires large high-pressure compressors or an arrangement of several compressors in parallel with high-capacity cooling systems.

2.6 Common Problems Encountered During Conversion

The conversion process on several ocean-going cargo vessels that I have supervised took on average between seven to ten working days. Common problems encountered during the conversion process were as follows.

1) Oil incompatibility: The working pressure of the new refrigerant is oftentimes higher, if the existing oil in the system is not compatible, it can lead to poor lubrication, reduced efficiency, and potential compressor damage and therefore requires a different type of lubricating oil known as “polyol-ester oil”, is to be used.

2) System leaks: The new refrigerant oftentimes operates at higher pressures, making it more prone to leaks, especially in older systems that might have worn or degraded seals and gaskets. Identifying and fixing these leaks is crucial to prevent refrigerant loss and ensure system efficiency.

3) Efficiency issues: The new refrigerant oftentimes has different thermodynamic properties. Systems not optimized for the new refrigerant might experience reduced efficiency, leading to increased energy consumption and decreased cooling capacity.

4) Performance mismatch: The new refrigerant oftentimes operates at different temperatures and pressures than the original refrigerant. This mismatch can affect the performance of the system components, including the compressor, expansion valves, and evaporator, leading to suboptimal performance.

5) Expansion valve problems: The new refrigerant oftentimes requires a different expansion valve or metering device due to its different pressure-temperature characteristics. If the existing expansion valve is not replaced or adjusted properly, it can lead to improper refrigerant flow and system inefficiency.

6) System contamination: Contaminants left in the system from the previous refrigerant can mix with the new refrigerant, leading to chemical reactions and clogs in the system components.

7) Inadequate system flushing: When converting a system, it's essential to thoroughly flush out the old refrige-rant, oil, and contaminants. Inadequate flushing can lead to a mixture of refrigerants and oils, causing system issues.
8) Insufficient charging: Correctly charging the system after conversion with the right amount of refrigerant is crucial for its efficient operation. Overcharging or undercharging can lead to performance problems.

III. CONCLUSION

In conclusion, our research paper delves into the critical realm of sustainable refrigerants within the context of marine engineering practice. The marine industry, essential for global trade and transportation, faces a pressing need to transition toward environmentally friendly refrigerants to mitigate the impact on our planet's climate. Through an extensive exploration of theoretical performance evaluations, this study has shed light on the various sustainable refrigerants available for marine applications.

Our findings highlight the pivotal role of refrigerants like R-744 (CO2), R-717 (Ammonia), R-407F, and R-407C, among others, in shaping the future of marine engineering. These refrigerants, with their low global warming potential (GWP) and minimal environmental impact, present promising alternatives to their high-GWP counterparts presently in use. Their implementation promises not only reduced greenhouse gas emissions but also enhanced energy efficiency and overall system performance.

However, our research also underscores the challenges associated with the adoption of sustainable refrigerants in marine engineering. Issues such as oil incompatibility, system leaks, efficiency concerns, and regulatory compliance pose significant hurdles. Addressing these challenges necessitates interdisciplinary efforts from engineers, policymakers, and industry stakeholders. It demands innovations in system design, rigorous adherence to safety protocols, and ongoing research to refine existing technologies and develop new, sustainable solutions.

As we move forward, the marine engineering community must remain proactive in embracing these sustainable refrigerants. Collaborative efforts between academia, industry, and regulatory bodies are essential to fostering a transition toward greener marine HVAC and refrigeration practices. By prioritizing environmental responsibility and adopting cutting-edge technologies, marine engineering can lead the way in building a more sustainable future for our planet.

In essence, this research paper serves as a foundation for informed decision-making within the marine engineering sector. By continuing to explore, innovate, and implement sustainable refrigeration technologies, we can navigate the challenges ahead and pave the way for a more environmentally conscious and efficient marine industry.

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