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Ammonia Reliability as Primary Refrigeration for Air Conditioning System

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Abstract

This paper explores the reliability and advantages of ammonia (R-717) as a primary refrigerant for air conditioning systems in comparison to hydrofluorocarbons (HFCs). With growing environmental concerns and stringent regulations targeting ozone-depleting substances and high global warming potential (GWP) refrigerants, ammonia emerges as a sustainable and efficient alternative. Ammonia offers zero ozone depletion potential (ODP) and near-zero GWP, coupled with superior thermodynamic properties that enhance energy efficiency and reduce operational costs. Despite its toxicity and flammability, advancements in safety protocols, system design, and operator training have significantly mitigated associated risks, enabling safe and dependable industrial and commercial applications. The study highlights ammonia's high latent heat of vaporisation, low boiling point, and favourable thermophysical characteristics that contribute to its outstanding coefficient of performance (COP) compared to HFCs. Furthermore, ammonia's environmental benefits are demonstrated through a substantial reduction in carbon emissions, with a Total Equivalent Warming Impact (TEWI) that is up to 68% lower than that of common HFC refrigerants. The paper also discusses the practical considerations for ammonia system safety, including risk assessment, leak detection, and emergency response measures aligned with international standards. While HFCs remain prevalent due to ease of handling and lower toxicity, their environmental impact and regulatory phase-down underscore the need for alternatives like ammonia. This comprehensive assessment supports ammonia's position as a reliable, eco-friendly, and economically viable refrigerant, aligning with global sustainability goals and future regulatory frameworks for air conditioning systems.

Keywords: ammonia, air conditioning, refrigerant reliability, energy efficiency, environmental sustainability

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1.0 INTRODUCTION

In the pursuit of sustainable and efficient refrigeration technologies, selecting the right refrigerant is crucial for optimising system performance, minimising environmental impact, and ensuring operational safety. Refrigeration is a process where heat is removed from a space or system by lowering and maintaining its temperature below the ambient temperature. Refrigeration is essential for advancing sustainable development because it supports a wide range of applications, including air conditioning, food storage, chemical manufacturing, and biomedical processes. Among the diverse refrigerants available today, ammonia refrigerant (R-717) and hydrofluorocarbons (HFCs) emerge as leading candidates, each offering unique benefits and presenting certain challenges. Although HFCs have gained traction due to their relatively low toxicity and user-friendly handling, ammonia continues to set the standard for reliability, energy efficiency, and environmental sustainability in both industrial and commercial refrigeration applications.

As regulations on chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and HFC refrigerants become increasingly strict, and with the complete phase-out of CFCs and HCFCs on the horizon, there is a strong focus on finding alternative refrigerants for existing refrigeration systems. These alternatives must not only possess thermodynamic properties like halocarbons but also be safe for both human health and the environment (Society of Heating & Engineers, 2002).

Ammonia stands out with its zero global warming potential (GWP) and zero ozone depletion potential (ODP), making it a far more environmentally responsible choice compared to HFCs, which often have GWPs ranging from several hundred to thousands. Additionally, ammonia's superior thermodynamic properties translate into outstanding energy efficiency, frequently surpassing that of HFC refrigerants, which leads to reduced operating costs and a smaller carbon footprint throughout the system's lifespan. (Pearson,2008).

Despite concerns related to ammonia toxicity and flammability, advancements in safety protocols, comprehensive operator training, and robust system engineering have rendered ammonia refrigeration systems exceptionally safe and reliable (Pearson, 2008). Conversely, HFC refrigerants, though generally safer in terms of toxicity, face drawbacks such as significant environmental impact (in the case of HFCs). Furthermore, ammonia's adaptability to large-scale industrial applications, including Heating, Ventilation, and Air Conditioning (HVAC) chillers, process cooling, and district cooling, further highlights its unparalleled reliability and durability.

This article presents a detailed comparison of ammonia and HFC, examining their respective strengths. It makes a compelling case for why ammonia remains the most dependable and advantageous refrigerant choice for air conditioning systems, supported by scientific evidence and extensive industry experience.

2.0 REFRIGERATION FOR AIR CONDITIONING SYSTEM

Refrigeration is a fundamental component in air conditioning systems, enabling the transfer of heat from indoor spaces to the external environment to maintain comfortable temperatures and humidity levels. Central to this process is the use of chemical substances that absorb and release heat as they circulate through the system's compressor, condenser, and evaporator. Two types of refrigerants used in air conditioning systems are ammonia (R-717) and HFC. Each has distinct characteristics that influence its application and environmental impact.

2.1 Ammonia

Ammonia is employed as an effective alternative to CFC-based refrigerants, which were banned in 1970 due to their adverse effects on the environment (Khudhur et al., 2022). Ammonia refrigerant (R-717) was among the earliest refrigerants utilised and continues to be commonly used in industrial refrigeration today (SensitronSrl, 2025). R717 has been introduced in refrigeration systems since the early 20th century. Ammonia (NH_3) is a chemical compound consisting of one nitrogen atom and 3 hydrogen atoms. Nitrogen is in Group 15 of the periodic table and has five valence electrons, enabling it to form covalent bonds with three hydrogen atoms. In this arrangement, NH_3 has no net charge, making it a neutral molecule without any positive or negative charges. In refrigeration systems, this neutral charge enables ammonia to circulate smoothly without causing disruption or reacting unexpectedly (Mike LaFollette, 2025).

Ammonia's high latent heat of vaporisation offers a key benefit over CFCs and HFCs by enhancing the coefficient of performance (COP) of refrigeration systems, leading to increased energy efficiency (Buhari et al., 2024a). Ammonia can absorb more heat during its phase change (from liquid to vapour) than most other refrigerants. This means the system requires a smaller mass of ammonia to achieve the same cooling effect, resulting in lower refrigerant charge and reduced stress on system components. NH_3's notably low boiling point of about -33.3°C reduces the number of compression stages required in the refrigeration cycle, boosting efficiency and leading to significant energy savings (Charge of NH3, n.d.). A properly designed ammonia refrigeration system achieves the same cooling capacity with seven to eight times less system circulation (Kuhlman, 2021).

One of ammonia's key advantages is its minimal environmental impact. Unlike synthetic refrigerants such as HFCs and HCFCs, ammonia is a naturally occurring gas that does not contribute to the greenhouse effect (Sharma, 2023). Ammonia is regarded as an environmentally friendly refrigerant with zero GWP and minimal ODP, making it a more sustainable option compared to HFCs, which pose greater environmental risks due to their higher GWP and flammability (Park et al., 2023). Potential cost savings come from lower spending on piping and installation. Ammonia's efficient properties allow the use of smaller diameter pipes. (Hayes, 2023). Table 1 presents the physicochemical properties of ammonia and compares them with those of other refrigerants. It is a comparison of ammonia, HCFCs, HFCs, and blended HFCs about GWP and ODP. It shows that ammonia has the lowest GWP and ODP.

Table 1: Physicochemical properties of ammonia and comparison with other refrigerants (Buhari et al., 2024b)

Refrigerant	Ammonia	Hydrochlorofluorocarbons (HCFCs)	Hydrofluorocarbons (HFCs)	Blend HFC
IUPAC Chemical Name	Ammonia	Chlorodifluoromethane	1,1,1,2-Tetrafluoroethane	1,1,1-Trifluoroethane, Pentafluoroethane, 1,1,1,2-Tetrafluoroethane
Chemical Formula	NH_3	$CHClF_2$	CF_3CH_2F	CF_3CH_2F, CF_3CH_3, CF_3CH_2F
ASHRAE Number	R-717	R-22	R-134a	R-404A
Physical State	Gas	Liquefied gas	Liquefied gas	Liquefied gas
Melting Point (°C)	-78	-160	-101	Not determined
Boiling Point (°C)	-33	-40.8	-26.06	-46.7
Critical Temperature (°C)	133	96.1	100.6	72.1
Water Solubility (g/l)	510 – 531	2.6	1.82	0.73
Latent Heat of Vaporisation at Boiling Point (kJ/kg)	1247.85	201.79	195.52	162.03
Flammable Limits (Lower / Upper)	16% / 25%	Not determined	Not determined	Not determined
GWP	>1	1820	1430	3260
ODP (100 Year)	0	0.055	0	0.20
Atmospheric Lifetime (years)	-	13.3	14.6	-

2.2 Hydrofluorocarbons (HFCs)

The adoption of HFCs has facilitated the swift elimination of ozone-depleting substances (ODS) such as halons, CFCs, and HCFCs, particularly in areas where alternative options were limited. HFCs have largely replaced the demand for ODS across various sectors, including refrigeration and air conditioning, insulating foams, propellants in metered dose inhalers, technical aerosols, specialised fire suppression systems, and other uses (Godwin & Ferenchiak, 2020a). HFCs have largely replaced the demand for ODS across various sectors, including refrigeration and air conditioning, insulating foams, propellants in metered dose inhalers, technical aerosols, specialised fire suppression systems, and other uses. As these technologies, especially refrigeration and air conditioning, continue to expand globally, the use and emissions of HFCs are projected to rise substantially (Godwin & Ferenchiak, 2020b).

HFCs are a class of refrigerants that have gained prominence in the refrigeration and air conditioning sectors due to their chemical composition, which includes carbon, fluorine, and hydrogen. Unlike their predecessors, CFCs and HCFCs, HFCs do not contain chlorine, which means they do not contribute to the depletion of the ozone layer. This characteristic has made HFCs a preferred choice in many applications, particularly in the European Union, where regulations have led to the banning of CFCs and HCFCs in various sectors since 2011 (Messineo, 2012). Besides their advantages in ozone layer protection, HFCs are not concerned about environment. They are potent greenhouse gases, which may lead to significant global warming. The refrigeration sector has been under pressure to transition from HFCs to more environmentally friendly alternatives due to their high GWP (Messineo, 2012). The energy consumption that is associated with refrigeration systems also plays a crucial role in greenhouse gas emissions, as the electricity is often generated by sources of fossil fuel, which further exacerbates climate change (Messineo, 2012).

HFCs are characterised by their high volatility and extremely low solubility in water. Once released into the environment, these substances primarily remain in the atmosphere. Regarding safety and health considerations, HFCs are widely utilised as refrigerants and fire suppression agents because they are generally non-flammable at room temperature and standard atmospheric pressure. Nevertheless, under certain conditions, HFCs can create flammable mixtures when combined with air. Compared to HCFCs, HFCs typically exhibit lower toxicity. Extensive toxicological assessments on commonly used HFCs have been carried out by the Program for Alternative Fluorocarbon Toxicity Testing (PAFTT) (Wen-Tien Tsai, 2005). It has long been understood that all organic chemicals have the potential to affect the environment. HFCs, which are also classified as volatile organic compounds (VOCs), exhibit particularly notable characteristics, most prominently their high volatility and hydrophobic nature compared to related substances like saturated chlorocarbons. As a result, the atmosphere is the primary reservoir where these compounds tend to accumulate following their release. It is widely acknowledged that HFCs are suitable substitutes for CFCs and HCFCs, as they share many comparable physical and thermochemical characteristics (Wen-Tien Tsai, 2005).

3.0 AMMONIA DEPENDABILITY IN THE AIR CONDITIONING INDUSTRY

Ammonia is increasingly recognised as a dependable refrigerant in the air conditioning industry due to its efficiency and low environmental impact. It is widely used in industrial refrigeration applications because of its properties of high energy efficiency, which results in lower operational costs for businesses. Ammonia has zero ODP and negligible GWP, which makes it an environmentally friendly choice compared to other synthetic refrigerants that can cause climate change and ozone layer depletion (Buhari et al., 2024c). Since it has zero ozone depletion and making it an attractive option for reducing greenhouse gas emissions in the air conditioning sector, this aligns with the global initiatives such as the Montreal Protocol, which aims to eliminate harmful refrigerants and promote alternatives that are less damaging to the environment. In addition, ammonia's low volumetric efficiency can limit its application in conventional vapour compression systems, although it is more suitable for sorption-based systems (Uddin & Saha, 2022). Moreover, the ongoing research regarding ammonia's physicochemical properties and its behaviour under various operating conditions is essential for improving its dependability as a refrigerant. Understanding the reactivity and safety characteristics of ammonia allows engineers and safety professionals to be aware of and improve risk assessment practices and regulations, ensuring that ammonia can be used safely in air conditioning systems and can reduce the risk to the operator (Buhari et al., 2024).

Ammonia is a highly efficient refrigerant, outperforming most HFCs and CFCs in terms of energy efficiency. It absorbs more heat per pound, allowing refrigeration systems using ammonia to operate with lower energy consumption. In contrast, systems relying on HFCs and CFCs typically need larger capacities to deliver the same cooling effect. This efficiency is largely due to ammonia's low boiling point of -28°F, which enables it to vaporise easily and absorb substantial heat during phase changes, thereby enhancing its cooling capacity. This characteristic allows ammonia systems to achieve effective heat exchange with less refrigerant mass. Traditional refrigerants like R-134a, however, have higher boiling points and lower latent vaporisation heat, limiting their heat absorption efficiency (Messineo, 2012). Another critical thermophysical property of ammonia is its phase change behaviour. Ammonia exhibits superior heat transfer performance during phase transitions, particularly during the processes of evaporation and condensation. These phase changes, where ammonia shifts between its liquid and gaseous states, are fundamental to the operation of vapour-compression refrigeration cycles. The high latent heat and consistent thermodynamic characteristics of ammonia during these transitions enhance the efficiency and reliability of refrigeration systems, making it a highly effective working fluid in thermal management applications. Ammonia adheres to classical saturation thermodynamic relationships, wherein a direct correlation exists between pressure and temperature under conditions of vapour-liquid equilibrium. This well-defined and predictable behaviour is fundamental to the design and operation of refrigeration systems, as it enables precise determination of the thermodynamic conditions required for optimal system performance. For example, at atmospheric pressure, ammonia reaches equilibrium between its vapour and liquid phases at a specific temperature, a characteristic that is critical for ensuring consistent efficiency and control within refrigeration cycles. Furthermore, ammonia exhibits relatively low density under standard conditions, with both its gaseous and liquid phases being less dense than air and water, respectively. This characteristic facilitates improved fluid dynamics within refrigeration systems, enabling efficient circulation and distribution of the refrigerant, thereby enhancing overall system performance (Ammonia Data Book 2nd Edition, 2008).

In addition, ammonia's high solubility in water presents both advantages and challenges in refrigeration applications. While this property can be leveraged in specific system designs, it also necessitates careful control measures to mitigate potential corrosion, particularly in environments where moisture is present. From a sustainability perspective, ammonia's composition, consisting solely of nitrogen and hydrogen, both naturally abundant elements, further supports its viability as an environmentally responsible refrigerant in line with current trends toward greener refrigeration technologies (Ammonia Data Book 2nd Edition, 2008).

4.0 RESULT OF DISCUSSION

4.1 Efficiency and Performance of Ammonia

The actual Coefficient of Performance (COP_{actual}) serves as an indicator of a cooling system's efficiency. It is determined by the ratio of the refrigeration effect to the work input by the compressor. Mathematically, it can be expressed as:

$$COP_{actual} : \frac{q_k}{w_k} = \frac{h_1 - h_4}{h_2 - h_1}$$

The refrigeration effect is the amount of heat that the refrigerant absorbs (q_k) from the environment or product being cooled. It is calculated by finding the difference in enthalpy between the evaporator outlet and inlet, where h_1 is the enthalpy at the evaporator outlet, and h_4 is the enthalpy at the evaporator inlet, both expressed in kJ/kg.

Compressor work (w_k) refers to the amount of heat absorbed by the refrigerant per unit mass during the refrigeration process. It is determined by the difference in enthalpy between the compressor outlet and inlet, where, h_1 is the enthalpy at the compressor inlet, and h_2 is the enthalpy at the compressor outlet, both measured in kJ/kg.

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This ratio effectively measures how efficiently the system utilises energy to transfer heat. In contrast, the ideal Coefficient of Performance (COP_{ideal}) reflects the theoretical upper limit of the refrigeration system's efficiency. It is calculated by dividing the evaporator temperature by the temperature difference between the condenser and evaporator, represented as:

$$COP_{ideal} = \frac{T_e}{T_c - T_e}$$

where *Te* denotes the evaporator inlet temperature and *Tc* represents the condenser inlet temperature.

The efficiency of the refrigeration machine is evaluated by comparing the actual COP to the ideal COP. It provides insight into how closely the system operates to its theoretical maximum efficiency. The formula used for this calculation is:

n = (COPactual/COPideal)×100%*n=COPactual/COPideal×100%* (Cholik et al., 2024)

The system efficiency over a 10-day period was calculated using Equation (Dharmavaram et al., 2023), and the results are presented in Fig. 1. Fig. 1 shows the efficiency values ranged from a minimum of 77% on Day 3 to a maximum of 91% on Day 5 align with the findings of (Wang et al., 2022) who conducted thermodynamic analyses of combined cooling and power systems and noted similar efficiency fluctuations based on varying operational parameters.

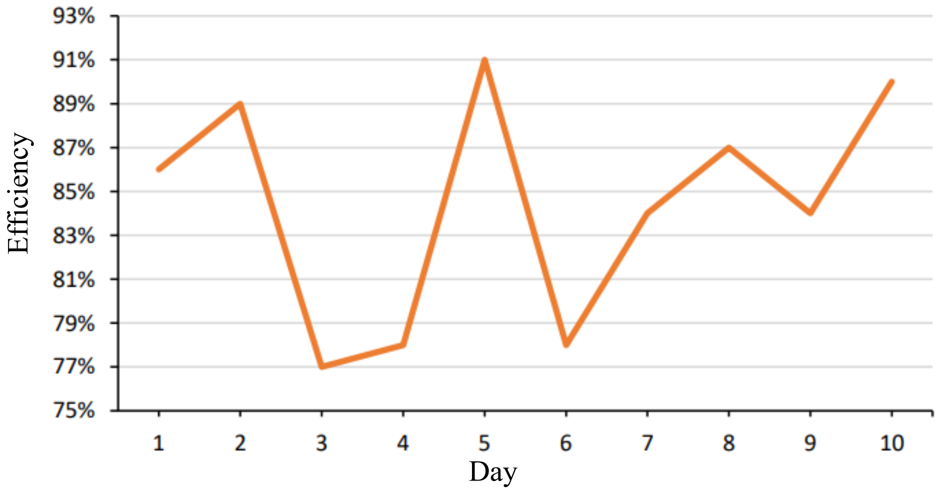

Fig. 1. Efficiency of the ammonia refrigeration system (Cholik et al., 2024)

4.2 Thermophysical Properties of Ammonia

Ammonia demonstrates distinctive thermophysical properties, namely thermal conductivity, specific heat, and viscosity, that are critical to its performance as a heat transfer fluid and its widespread use in industrial processes. These properties are strongly temperature and phase-dependent, which enhances ammonia's versatility in thermal systems. In both gaseous and liquid phases, ammonia exhibits relatively high thermal conductivity, significantly contributing to its superior heat transfer capabilities compared to many other substances. Furthermore, its high specific heat in both phases reinforces its effectiveness in absorbing and transporting thermal energy. Although the viscosity of ammonia, in either phase, is generally moderate relative to other fluids, it remains within a suitable range for efficient circulation in thermal systems. Fig. 2 shows the specific heat of ammonia liquid. The graph displays how the specific heat (in Btu/lb·°F) of a saturated liquid changes with temperature (in °F).

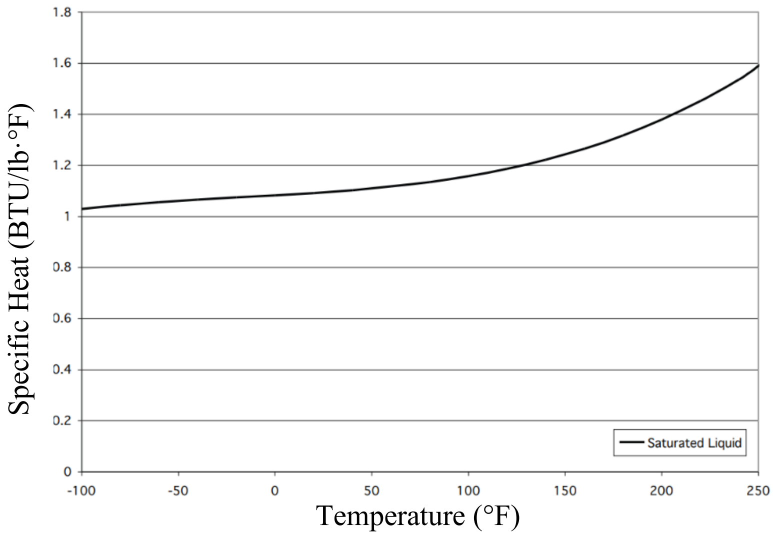

Fig. 2. Specific Heat of Ammonia Liquid (Ammonia Data Book 2nd Edition, 2008)

Ammonia in its gaseous state exhibits high thermal conductivity (k) compared to most other substances. This property makes ammonia highly effective for heat transfer applications. Fig. 2 shows the thermal conductivity values of ammonia in its liquid form and in its gas/vapour form.

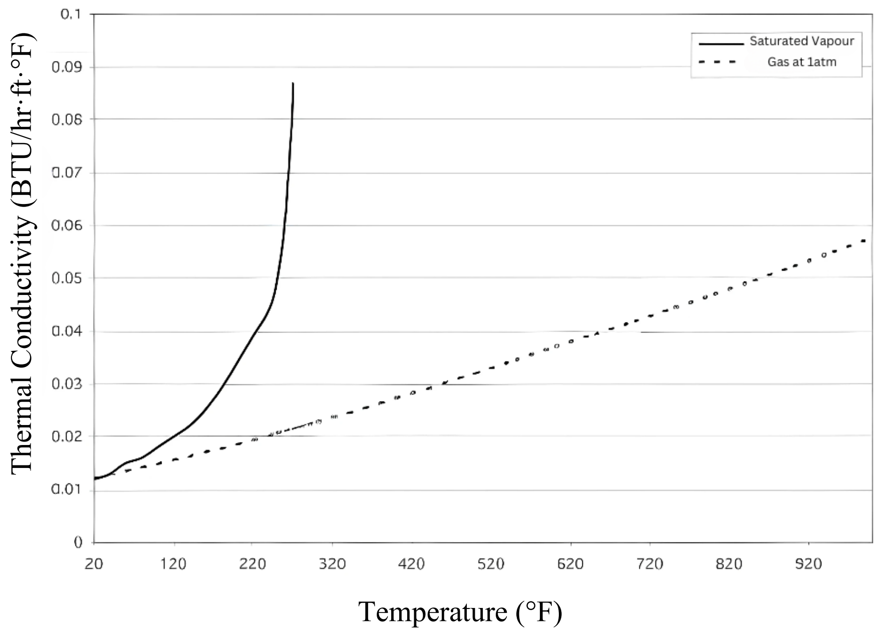

Fig. 3. Thermal Conductivity of Ammonia Gas/Vapour (Ammonia Data Book 2nd Edition, 2008)

The viscosity (μ) of ammonia, both as a liquid, is approximately average when compared to other fluids. Fig. 4 shows the following graphs for the viscosity values of ammonia in its liquid form.

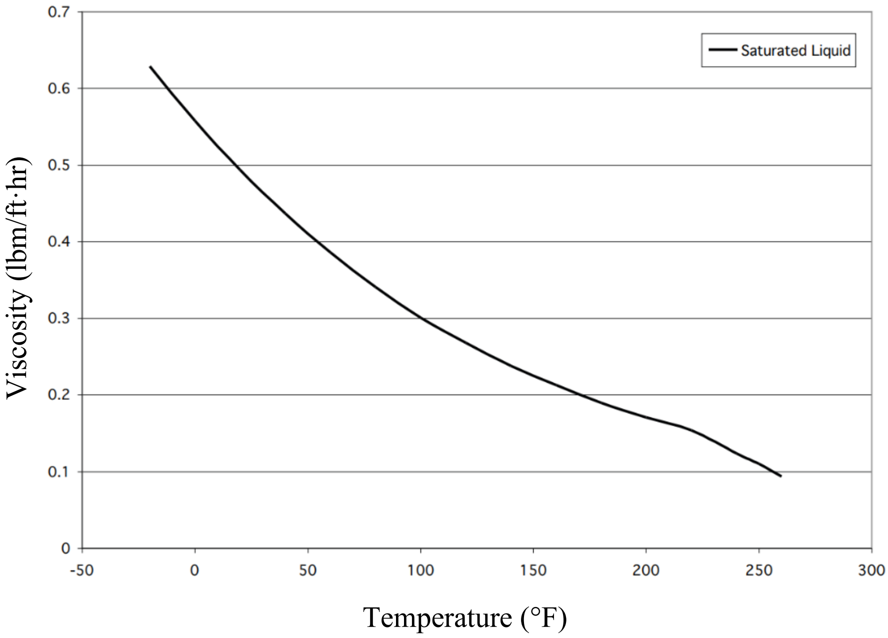

Fig. 4. Viscosity of Ammonia Liquid (Ammonia Data Book 2nd Edition, 2008)

4.3 Safety and Handling

Ammonia is widely recognised as an effective primary refrigerant due to its high efficiency and low environmental impact. However, its use comes with significant safety considerations that must be addressed to ensure safe handling and operation. Firstly, risk assessment and prevention are important. The first step in ensuring safety is to conduct a thorough risk assessment of the ammonia refrigerating system. This involves identifying potential hazards associated with ammonia, such as leaks or exposure, and implementing preventive measures to mitigate these risks. (Lamberg et al., 2015). The safety guide emphasises the importance of assessing and preventing various risks associated with ammonia systems to promote safe operation. Moreover, incident management. Effective incident management is crucial for minimising the consequences of ammonia leaks or other emergencies. The safety guide highlights the importance of having a clear plan for managing incidents, including the use of gas sensors and proper ventilation in areas where ammonia is present. This can help detect leaks early and prevent the buildup of hazardous concentrations of ammonia (Lamberg et al., 2015).

Suppliers are required to train staff in the operation and safety of ammonia refrigeration systems according to European Standard SFS-EN 378, which includes understanding equipment, following instructions, and complying with safety measures (Khudhur et al., 2022). Systems must have isolation valves to minimise hazards and leaks, gas sensors monitored at control panels for quick leak detection, and pressure relief valves on pressurised parts to prevent overpressure. Suppliers must also provide key information such as contact details, system operation instructions, refrigerant type and levels, diagrams, handling and safety procedures, PPE requirements, first aid steps, and ammonia safety data sheets. Safe operating limits, including minimum and maximum design pressures, must be set before use, ensuring no part exceeds the pressure rating of its weakest component. In case of an ammonia leak, management must have emergency protocols for detection, alarms, PPE use, evacuation, and system shutdown, with staff trained to respond quickly and safely. During a leak, follow DOSH guidelines: secure and isolate the area, evacuate upwind, use barriers and windsocks, restrict access, call trained responders, and monitor ammonia levels to manage the situation. Control rooms should be located outside the main process area, with system data linked to control panels and vibration sensors on major equipment to detect problems early (Khudhur et al., 2022).

4.4 Environmental Impact and Regulatory Context

The Total Equivalent Warming Impact (TEWI) model was employed to evaluate the carbon emissions linked to both refrigerants. The findings revealed that Ammonia's TEWI is 68.1% lower than that of R404A. This indicates that Ammonia not only offers superior energy efficiency but also substantially lowers environmental impact, positioning it as a more sustainable choice for refrigeration (Dreepaul et al., 2020).

Fig. 5 shows the CO_2 gas released into the atmosphere by refrigerants as an alternative to R22 gas. The current system using R22 gas emits approximately 95 kg of CO_2 annually. Among alternative refrigerants, R717 stands out as the one with the lowest CO_2 emissions, releasing only 78.62 kg per year from the generators. The CO_2 emissions from other refrigerants are as follows: 96.28 kg for R1234yf, 93.38 kg for R161, 87.23 kg for R245fa, 87.02 kg for R453A, and 110.7 kg for R407C. Notably, R407C is the refrigerant associated with the highest CO_2 emissions (Durmusoglu & Kocak, 2023).

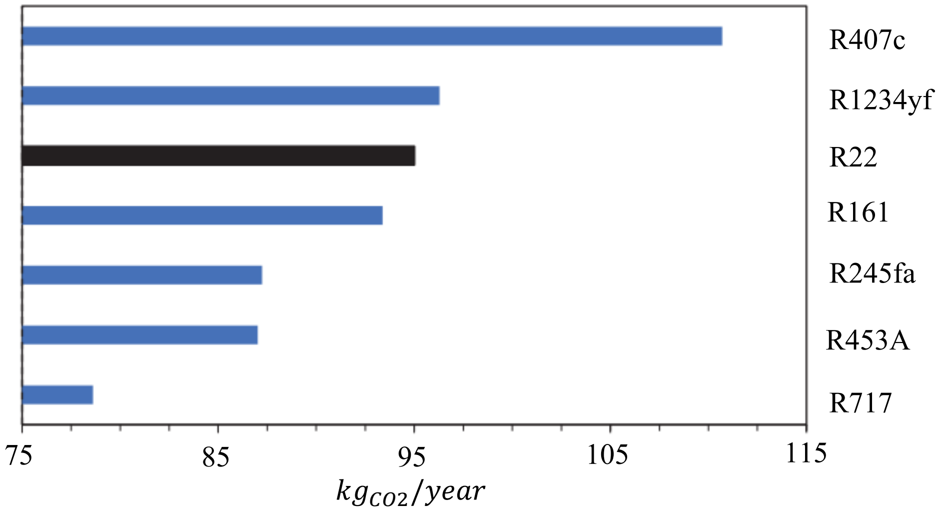

Fig. 5. CO_2 gas released to the atmosphere by refrigerants as an alternative to R22 gas. (Durmusoglu & Kocak, 2023)

5.0 SUMMARY

The article presents a detailed assessment of ammonia as a reliable and sustainable primary refrigerant for air conditioning systems, particularly considering global efforts to mitigate climate change and phase out high-GWP substances. Ammonia refrigerant (R-717), with its zero ODP and zero GWP, stands out as an environmentally friendly alternative to conventional refrigerants. It has been widely used in industrial refrigeration for over a century, with a proven track record of operational reliability and thermal efficiency. Its superior thermodynamic properties enable systems to operate with lower energy consumption and reduced operational costs. These characteristics make ammonia not only a cost-effective solution but also one aligned with future regulatory and sustainability goals. Despite its toxicity and mild flammability, the article highlights that with proper system design, handling protocols, and safety measures, ammonia-based systems can operate safely and efficiently, even in commercial and semi-commercial applications. The study also compares ammonia with HFCs, which, while chemically stable and less toxic, are associated with moderate to high GWP. HFCs continue to be used in many applications due to their compatibility with existing systems and ease of use, making them a practical choice during the transition to greener refrigerants. However, with increasing environmental regulations such as the Kigali Amendment and regional climate action policies, the use of high-GWP refrigerants like HFCs is expected to decline. The article stresses that ammonia's environmental benefits, long-term economic advantages, and compliance with future regulations make it a strong candidate for wider adoption in the air conditioning sector. Furthermore, it explores how the current regulatory context, including environmental impact assessments, supports the push for low-impact refrigerants like ammonia. In summary, while HFCs serve as convenient short- to medium-term solutions, ammonia presents a compelling case as a future-proof, eco-efficient refrigerant that supports both environmental responsibility and operational performance.

REFERENCES

Ammonia Data Book 2nd Edition. (2008). *Chapter Two: Properties of Ammonia Physical Properties*.

Buhari, J., Najib Jaafar, M., & Rosli, I. (2024). *Optimising Ammonia Safety in Industrial Refrigeration Applications: A 2 Review of Risk Assessment Practices and Regulations*. *Charge Of NH3*.

Cholik, A., Ruhyat, N., & Novianto, S. (2024). Performance Evaluation of Ammonia Refrigeration Systems in a Texturizing Plant. *International Journal of Innovation in Mechanical Engineering and Advanced Materials*, *6*(3), 161.

Dreepaul, R. K., Rughoo, D., & Busawon, K. (2020). A comparative assessment of R404A and Ammonia (R717) in an industrial Set-up. *2020 3rd International Conference on Emerging Trends in Electrical, Electronic and Communications Engineering, ELECOM 2020 - Proceedings*, 147–152.

Durmusoglu, Y., & Kocak, G. (2023). The Comparative Analysis of Alternative Refrigerants on Ship Refrigeration Systems: Performance, Environmental, and Economic Approach. *Pomorstvo*, *37*(2), 240–254.

Godwin, D. S., & Ferenchiak, R. (2020a). The implications of residential air conditioning refrigerant choice on future hydrofluorocarbon consumption in the United States. *Journal of Integrative Environmental Sciences*, *17*(3), 29–44.

Hayes, C. (2023, June 5). *Ammonia-CO2 AC Can Cut Costs, Energy Use and Emissions*.

Khudhur, D. A., Tuan Abdullah, T. A., & Norazahar, N. (2022). A Review of Safety Issues and Risk Assessment of Industrial Ammonia Refrigeration System. In *ACS Chemical Health and Safety* (Vol. 29, Issue 5, pp. 394–404). American Chemical Society.

Kuhlman, R. (2021, December 2). *Why Use Ammonia as a Refrigerant? - Kuhlman, Inc.*

Lamberg, S., Lautkaski, R., & Virolainen, K. (2015). *Safety Guide of Ammonia Refrigerating Systems Translation of the second Finnish edition by Risto Lautkaski*

Messineo, A. (2012). R744-R717 Cascade refrigeration system: Performance evaluation compared with a HFC two-stage system. *Energy Procedia*, *14*, 56–65.

Mike LaFollette. (2025, May 12). *Understanding the Charge of NH3 in Industrial Refrigeration Systems*.

Park, K. H., Lee, J. W., & Seo, Y. (2023). Design of cascade refrigerant process utilizing CO2 and NH3 to remove volatile organic compounds. *Journal of CO2 Utilization*, *70*.

Pearson, A. (2008). Refrigeration with ammonia. In *International Journal of Refrigeration* (Vol. 31, Issue 4, pp. 545–551).

SensitronSrl. (2025). *Ammonia and gas detection: refrigeration systems*.

Sharma, S. (2023, August 2). *Ammonia as a Refrigerant: Efficient and Eco-Friendly Choice*.

Society of Heating, A., & Engineers, A.-C. (2002). *A N I N T E R N A T I O N A L O R G A N I Z A T I O N ASHRAE Position Document on AMMONIA AS A REFRIGERANT*.

Uddin, K., & Saha, B. B. (2022). An Overview of Environment-Friendly Refrigerants for Domestic Air Conditioning Applications. In *Energies* (Vol. 15, Issue 21). MDPI.

Wen-Tien Tsai. (2005, March 23). *An overview of environmental hazards and exposure risk of hydrofluorocarbons (HFCs). Chemosphere, 61(11), 1539–1547|10.1016/j.chemosphere.2005.03.084*.