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ANALYSIS OF THE ECONOMIC EFFICIENCY OF REPLACING REFRIGERANTS WITH PROPANE IN INDUSTRIAL REFRIGERATION SYSTEMS

АНАЛИЗ ЭКОНОМИЧЕСКОЙ ЭФФЕКТИВНОСТИ ЗАМЕНЫ ХЛАДАГЕНТОВ ПРОПАНОМ В ПРОМЫШЛЕННЫХ ХОЛОДИЛЬНЫХ СИСТЕМАХ

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Аннотация. В данном исследовании оценивается экономическая эффективность замены традиционных хладагентов на пропан (R290) в промышленных холодильных системах. Сравнивается пропан с традиционными хладагентами по различным критериям. Анализ охватывает первоначальные инвестиции и экономию эксплуатационных расходов, а также повышение энергоэффективности и соблюдение экологических норм. На основе опыта российских и американских компаний в статье рассмотрено успешное внедрение пропана в различные отрасли промышленности. Подчеркивается, что пропан является экономически эффективной и устойчивой альтернативой традиционным хладагентам, однако его использование требует строгих мер безопасности из-за его воспламеняемости. Кроме того, исследование подчеркивает потенциал существенных долгосрочных экономических выгод от снижения затрат на техническое обслуживание, связанных с пропановыми системами. Также исследуется масштабируемость внедрения пропана в различных промышленных условиях, демонстрируя его адаптируемость. Представлен всесторонний обзор нормативных стимулов, которые поддерживают переход на пропан, что еще больше повышает его экономическую привлекательность.

Annotation. This study evaluates the economic efficiency of replacing traditional refrigerants with propane (R290) in industrial refrigeration systems. It compares propane with traditional refrigerants across various criteria. The analysis covers initial investments and operational cost savings, as well as enhanced energy efficiency and compliance with environmental regulations. Based on the experiences of Russian and American companies, the paper examines successful implementations of propane in various industrial sectors. It is emphasized that propane is an economically efficient and sustainable alternative to traditional refrigerants; however, its use necessitates stringent safety measures due to its flammability. Additionally, the research highlights the potential for substantial long-term economic benefits from the reduced maintenance costs associated with propane systems. The study also explores the scalability of propane implementation in diverse industrial settings, demonstrating its adaptability. Finally, it provides a comprehensive overview of regulatory incentives that support the transition to propane, further enhancing its economic appeal.

Ключевые слова: пропан, промышленное охлаждение, экономическая эффективность, хладагенты, энергоэффективность, соблюдение экологических требований, тематические исследования.

Keywords: propane, industrial refrigeration, economic efficiency, refrigerants, energy efficiency, environmental compliance, case studies.

Introduction

Refrigerants play an important role in industrial refrigeration systems, ensuring the effective and efficient cooling required for various industrial processes. Historically, a wide range of refrigerants has been utilized, including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs). These substances have been favored due to their thermodynamic properties and efficiency. However, the environmental implications of these traditional refrigerants have become a significant concern. CFCs and HCFCs have been identified as major contributors to ozone layer depletion, while HFCs, although less harmful to the ozone layer, possess high global warming potential (GWP). The widespread use of these refrigerants has prompted international regulations aimed at phasing out substances with high ODP and GWP.

The environmental issues associated with conventional refrigerants underscore the necessity for more sustainable alternatives. Propane has emerged as a promising candidate due to its low GWP, zero ODP, and favorable thermodynamic characteristics. Despite its advantages, the adoption of propane in industrial refrigeration systems poses challenges, primarily related to its flammability and associated safety concerns. The goal of this research is to conduct an analysis of the economic efficiency of replacing traditional refrigerants with propane in industrial refrigeration systems.

Main part. Overview of traditional refrigerants and their environmental impact

Traditional refrigerants have played a pivotal role in the development and operation of industrial refrigeration systems, facilitating essential cooling processes across various sectors, including food preservation, chemical manufacturing, and air conditioning. The historical use of refrigerants in the industry can be traced back to the late 19th and early 20th centuries with the introduction of ammonia (NH_3) and carbon dioxide (CO_2), which were among the first substances used for industrial cooling due to their favorable thermodynamic properties. However, the toxicity and high-pressure requirements of these early refrigerants necessitated the search for safer and more efficient alternatives.

The advent of CFCs in the 1930s marked a significant advancement in refrigeration technology. CFCs, such as R-12 and R-11, were widely adopted due to their non-toxicity, non-flammability, and excellent stability. These properties made them ideal for a range of applications, leading to their pervasive use in both industrial and domestic refrigeration [1]. However, the environmental impact of CFCs became evident in the 1970s when scientists discovered their role in ozone layer depletion. This revelation led to the implementation of international regulations, most notably the Montreal Protocol in 1987, which mandated the phase-out of ozone-depleting substances.

In response to the phase-out of CFCs, HCFCs and HFCs were developed as transitional alternatives. HCFCs, such as R-22, offered lower ODP compared to CFCs but were still environmentally harmful. Consequently, HCFCs were also targeted for phase-out under subsequent amendments to the Montreal Protocol. HFCs, such as R-134a and R-410A, emerged as the next generation of refrigerants, characterized by zero ODP. However, HFCs possess high GWP, contributing significantly to climate change. The growing recognition of their environmental impact has spurred further regulatory actions, including the Kigali Amendment to the Montreal Protocol in 2016, which aims to reduce the production and consumption of HFCs globally.

The historical evolution of refrigerants reflects a continuous effort to balance performance with environmental stewardship. Despite their efficiency and widespread use, traditional refrigerants have imposed severe ecological costs, necessitating the development of more sustainable alternatives [2]. The ongoing transition towards environmentally benign refrigerants, such as natural substances and low-GWP synthetic options, underscores the industry's commitment to mitigating environmental harm while maintaining the critical functions of industrial refrigeration systems.

Propane as an alternative refrigerant

As a hydrocarbon, propane exhibits several key advantages that make it an attractive option for replacing traditional refrigerants:

•**Low GWP**: it has a significantly lower GWP compared to traditional refrigerants such as HFCs and HCFCs, contributing minimally to global warming. Propane has a GWP of only 3, compared to R-134a (HFC) with a GWP of 1430 and R-22 (HCFC) with a GWP of 1810 [3].

•**Zero ODP**: it does not contribute to ozone layer depletion, addressing a major environmental concern associated with CFCs and HCFCs.

•**High energy efficiency:** its thermodynamic properties enable efficient heat exchange, leading to improved system performance and lower energy consumption.

•**Widespread availability:** as a byproduct of natural gas processing and petroleum refining, propane is readily available and cost-effective for industrial applications.

From a thermodynamic perspective, propane offers several advantages that enhance the efficiency of refrigeration systems. Propane's critical temperature is 96.7°C, and its critical pressure is 42.5 bar, allowing for efficient heat exchange and improved system performance. It has a latent heat of vaporization of 356 kJ/kg, which is higher compared to traditional refrigerants like R-134a, which has a latent heat of vaporization of approximately 215 kJ/kg. This higher latent heat translates to better cooling capacity per unit of refrigerant. This efficiency can result in up to 10-20% lower energy consumption and operating costs for industrial refrigeration systems [4].

The global propane market has been experiencing consistent annual growth, driven by increasing demand for cleaner energy alternatives, the versatility of propane in various industrial applications, and the ongoing shift towards environmentally sustainable refrigerants (fig.1).

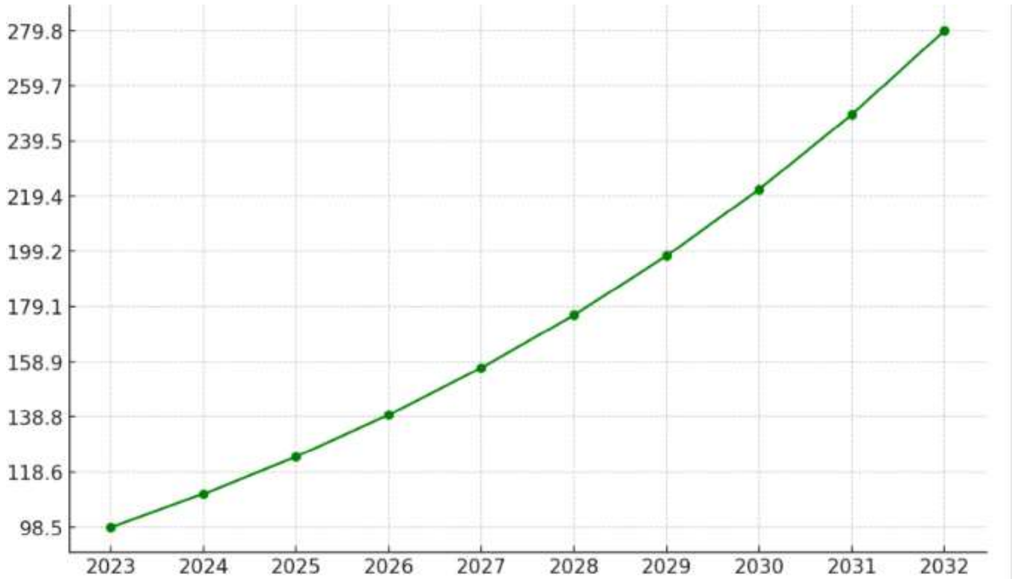

Figure 1. Projected global propane market growth, billion dollars [5]

North America holds the largest share of the global propane market, with the USA being the leading consumer. Currently, approximately 50% of rural areas in the USA rely on propane for household needs. The Asia-Pacific region is projected to experience the fastest growth during the forecast period, driven by increasing demand from China, India, and other developing countries. The compound annual growth rate (CAGR) of liquefied propane and butane production in Russia for the period 2017-2023 was 2.5%. In 2023, Russian enterprises produced 17,806 thousand tons of liquefied propane and butane, which is 9.6% higher compared to the results of 2022 [6].

Economic analysis

Evaluating the economic feasibility of transitioning from traditional refrigerants to propane in industrial refrigeration systems is essential for informed decision-making. Traditional refrigerants, despite their effectiveness, entail substantial environmental and regulatory costs that can significantly impact overall economic performance. In contrast, propane emerges as a potentially cost-effective and environmentally sustainable alternative (table 1).

Table 1. Economic comparison of propane and traditional refrigerants

Parameter	Propane (R-290)	Traditional Refrigerants (R-134a, R-22)
Initial investment costs for switching to propane	Typically, lower due to lower refrigerant cost and fewer modifications required for existing systems. Additional costs may include safety equipment and training.	Higher due to the cost of refrigerants and the need for more extensive system modifications and compliance with regulations.

Operational and maintenance cost comparison	Generally lower due to propane's high energy efficiency, leading to reduced electricity consumption. Maintenance is moderate with periodic safety checks.	Higher operational costs driven by lower energy efficiency. Maintenance costs can be significant due to stricter environmental regulations and potential leakage.
Cost-benefit analysis over the system's lifecycle	Lower lifecycle costs, considering propane's lower purchase price, high efficiency, and minimal environmental fees. The initial investment is quickly offset by savings.	Higher lifecycle costs due to higher initial investment, greater energy consumption, and ongoing compliance costs with environmental regulations.
Analysis of energy efficiency and operational costs	Propane systems benefit from higher energy efficiency, resulting in up to 10-20% lower operational costs. This translates into significant savings over time.	Systems using traditional refrigerants are less efficient, leading to higher operational costs and greater energy consumption.
Long-term economic benefits of switching to propane	Long-term benefits include reduced total cost of ownership, lower energy bills, and avoidance of environmental impact fees. Propane's environmental benefits also position businesses favorably in terms of regulatory compliance and corporate social responsibility.	The long-term economic outlook is less favorable due to ongoing regulatory pressures, potential future bans or restrictions, and higher operational costs. Businesses may face increasing costs associated with environmental compliance and carbon taxes.

The economic analysis underscores the environmental benefits of transitioning to propane as a refrigerant. The reduction in greenhouse gas emissions and the elimination of ozone-depleting substances position propane as an important player in achieving long-term sustainability goals, making it an attractive option for companies looking to improve their environmental footprint [7].

While the benefits of propane are substantial, the risk assessment associated with its use is a consideration. Propane's flammability necessitates stringent safety measures to ensure safe operation and handling. These measures include the implementation of explosion-proof equipment, proper ventilation systems, and regular safety training for personnel. The initial investment in safety equipment and protocols may offset some of the cost savings; however, the long-term benefits of reduced environmental impact and lower operating costs can outweigh these initial expenditures. Effective risk management strategies are essential to mitigate the hazards associated with propane, ensuring that its adoption in industrial refrigeration systems is both economically viable and safe.

Propane in industrial refrigeration systems

In Russia, the food processing industry has seen significant advancements with the use of propane in refrigeration systems. For instance, the Miratorg Agribusiness Holding, one of Russia's leading meat producers, transitioned to propane-based refrigeration systems in their processing facilities. This shift resulted in a notable reduction in energy consumption and operational costs. The enhanced energy efficiency of propane systems allowed Miratorg to achieve a decrease in electricity usage, which not only reduced their operational expenses but also contributed to their sustainability goals by lowering greenhouse gas emissions.

Another noteworthy example in Russia is the implementation of propane-based refrigeration systems by Rusagro Group, one of the largest vertically integrated agricultural companies in the country. Rusagro has adopted propane as a refrigerant in several of its meat processing and storage facilities. This transition was driven by the need to enhance energy efficiency and reduce the environmental impact of their operations.

The switch to propane has yielded significant benefits for Rusagro [8]. The company reported a reduction in energy consumption across its facilities, which translated into substantial cost savings. The improved thermodynamic properties of propane allowed for more efficient heat exchange processes, leading to enhanced overall system performance. Additionally, the adoption of propane has enabled Rusagro to align with international environmental standards, reducing their carbon footprint and contributing to global sustainability efforts.

Rusagro's experience underscores the importance of integrating advanced safety protocols to mitigate the flammability risks associated with propane. The company invested in comprehensive safety measures, including the installation of explosion-proof equipment, rigorous training programs for staff, and the implementation of continuous monitoring systems to detect any potential leaks. These proactive steps ensured that the transition to propane was not only economically beneficial but also safe and reliable.

In the USA, a prominent example is the use of propane by Lineage Logistics, a leading provider of temperature-controlled logistics solutions. Lineage Logistics retrofitted several of its cold storage facilities with propane-based refrigeration systems. The transition led to improved cooling performance and significant cost savings [9]. The company reported a reduction in energy consumption, highlighting propane's superior thermodynamic properties. Additionally, the switch to propane helped Lineage Logistics comply with stringent environmental regulations, avoiding potential fines and positioning the company as a leader in sustainable practices within the industry.

Another notable example is Leer Inc., a leading manufacturer of temperature-controlled storage solutions. Leer Inc. has committed to transitioning entirely to propane (R290) as a refrigerant in their product offerings. As of January 1, 2024, Leer Inc. will no longer produce ice merchandisers or ice vending machines using R404a refrigerant and will exclusively use R290. This change is part of Leer Inc.'s strategy to enhance performance, comply with environmental regulations, and meet customer demand for more sustainable refrigerant options.

Propane's low GWP of 3 makes it an environmentally friendly alternative to R404a, which has a GWP of 3,900. This significant reduction in GWP helps Leer Inc. align with forthcoming regulations that enforce a maximum GWP limit of 150 for refrigerants, set to take effect nationwide in the USA in 2025 [10].

Leer Inc.'s adoption of R290 is driven by its high performance and eco-friendly properties, which have proven successful in their applications. The company reports increased efficiency and compliance with both state and federal regulations, positioning itself as a leader in sustainable refrigeration solutions.

Conclusions

The economic analysis of replacing traditional refrigerants with propane (R-290) in industrial refrigeration systems reveals significant advantages in terms of cost efficiency, environmental benefits, and regulatory compliance. Propane offers lower initial investment and operational costs due to its high energy efficiency, which can result in up savings in energy consumption. Propane's low GWP and zero ODP significantly reduce environmental compliance costs and position it as a sustainable alternative in line with global environmental regulations. The successful adoption of propane underscores the importance of integrating advanced safety protocols to mitigate flammability risks, ensuring both economic viability and safety.

The findings support the adoption of propane as a cost-effective and environmentally sustainable refrigerant, offering long-term economic benefits and aligning with future regulatory requirements aimed at reducing greenhouse gas emissions and promoting sustainability in industrial refrigeration systems.

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