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NATURAL REFRIGERANT-BASED COOLING SYSTEM DESIGN REDUCES CARBON EMISSIONS IN HVAC TECHNOLOGY

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ABSTRACT

This study aims to analyze and design a natural refrigerant-based cooling system as an effort to reduce carbon emissions in HVAC technology without reducing system performance. The research method used is a qualitative method with a descriptive-exploratory design, which was chosen to understand in depth the system design process, technical considerations, and environmental implications of the use of natural refrigerants. This approach is considered appropriate because it allows for integration between theoretical concepts and sustainable cooling system design practices. The research was carried out at the Center for Research and Engineering of Air Conditioning and Refrigeration Systems, Faculty of Engineering, University of Indonesia, Depok. The research informants totaled six people who were selected purposively, consisting of HVAC system designers, operational managers, mechanical engineering academics, energy efficiency practitioners, environmental specialists, and technical policy analysts, who were selected because they had relevant experience and competencies. The results show that the design of a natural refrigerant-based cooling system has the potential to reduce energy consumption and carbon emissions without sacrificing the performance of the HVAC system. This study recommends the development of integrated system design as well as policy support to encourage the adoption of environmentally friendly refrigeration technologies.

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INTRODUCTION

The development of the building sector and modern industry shows an increasing dependence on heating, ventilation, and air conditioning (HVAC) systems to support thermal comfort and process stability. In various countries, the energy consumption of HVAC systems is recorded as one of the largest contributors to electricity use, especially in commercial buildings, industrial facilities, and high-density urban areas. This condition makes HVAC technology not only seen as a supporting mechanical system, but also as a strategic element in the issue of energy efficiency and global carbon emission control. As climate change awareness increases, the pressure on the engineering sector to produce more environmentally friendly cooling systems is getting stronger(J. Chen et al., 2025).

The main problem in conventional HVAC systems lies in the use of synthetic refrigerants that have the potential for global warming and significant environmental impacts. Hydrofluorocarbon-based refrigerants and other synthetic compounds are widely used due to their thermal stability and good cooling performance. However, these characteristics are accompanied by negative impacts in the form of contributions to global warming, increased carbon footprints, and environmental risks in the event of a leak in the system. In this context, the development of refrigeration technology is no longer enough to be only oriented towards capacity and reliability, but must also consider aspects of environmental sustainability and long-term safety(Banerjee et al., 2023).

The global push towards a clean energy transition is driving the emergence of green technology approaches in the field of refrigeration system engineering. Green technology emphasizes the use of

resources that are safer, more efficient, and have minimal environmental impact without sacrificing the technical performance of the system. One approach that has received widespread attention is the use of natural refrigerants, such as hydrocarbons, carbon dioxide, and ammonia, which are naturally present in the environment and have a much lower global warming potential than synthetic refrigerants. Natural refrigerants are considered to be able to be a strategic solution to reduce carbon emissions while improving the energy efficiency of HVAC systems(Nawar et al., 2023).

Although conceptually natural refrigerants have long been known, their implementation in modern refrigeration systems still faces a variety of technical and design challenges. The thermophysical characteristics of natural refrigerants that differ from synthetic refrigerants demand a more careful approach to system design, especially with regard to operating pressure, safety aspects, and material compatibility. These challenges are often the reason why the adoption of natural refrigerants has been relatively slow, especially in developing countries that still rely on conventional HVAC technology. Therefore, a study of the design of the cooling system is needed that not only emphasizes the theoretical aspect, but also the applicative and contextual(Kumari & Nayak, 2023).

State of the art research in the field of sustainable refrigeration systems shows that there is an increasingly strong paradigm shift from the use of synthetic refrigerants to the use of natural refrigerants as the main alternative. This shift is triggered by increasing global attention to climate change issues, reducing greenhouse gas emissions, and higher energy efficiency demands in the building and industrial sectors. In recent decades, various studies have examined the thermodynamic characteristics of natural refrigerants, such as heat transfer ability, operating pressure, and cooling system performance coefficients. The results of these studies generally show that natural refrigerants have the potential for competitive energy efficiency as well as lower environmental impact than conventional synthetic refrigerants(Yan & Tang, 2024).

In addition to the thermodynamic aspect, a number of studies have also highlighted the environmental advantages of natural refrigerants through the analysis of global warming potential and its contribution to reducing carbon emissions. Natural refrigerants are considered more in line with the principles of green technology because they come from compounds that are naturally present in the environment and do not cause significant long-term impacts on the atmospheric layer. This approach is in line with global policies that encourage the use of environmentally friendly technologies as part of climate change mitigation strategies. Thus, the exploration of natural refrigerants is not only seen as a technical issue, but also as part of a broader sustainability agenda(Wang et al., 2025).

Nevertheless, although the literature shows a positive tendency towards the use of natural refrigerants, most of the existing research still focuses on simulation analysis or laboratory testing on a limited scale. This approach is important for understanding the basic characteristics and technical potential of natural refrigerants, but it is often not able to represent the complexity of real operational conditions in HVAC systems. Factors such as variations in cooling loads, environmental fluctuations, and interactions between system components are often not fully accommodated in small-scale studies. As a result, the gap between research results and practical implementation is still quite wide(Tber, 2023).

Another limitation seen in the state of the art is the tendency of research to be partial. Many studies focus on one specific aspect, such as energy efficiency or environmental analysis, without integrating them simultaneously with the overall design of the cooling system. In fact, the performance of HVAC systems is the result of a complex interaction between component design, refrigerant characteristics, and operating strategy. When these aspects are analyzed separately, the resulting recommendations are often less applicable and difficult to adopt by practitioners in the field(Ahmad, 2024).

The main problem of this research arises from the need to bridge the gap between the normative concept of green technology and its application in the design of practical, efficient, and scalable HVAC systems. Although the environmental advantages of natural refrigerants have been widely affirmed in the literature, there are still limited studies that comprehensively examine how the design of natural refrigerant-based refrigeration systems can be optimized to achieve performance that is equal to or even surpass conventional systems. The absence of an integrated design approach means that the potential of natural refrigerants has not been fully explored(Ding & Jia, 2024).

This condition has an impact on the emergence of doubts among HVAC practitioners and industry players regarding the technical and economic feasibility of the application of natural

refrigerants. Concerns related to safety, operational stability, and implementation costs are often the main barriers to the adoption of this technology. In the absence of an applicative system design study based on thorough performance evaluation, natural refrigerants tend to be seen as conceptually ideal solutions but difficult to implement practically. Therefore, research that can provide empirical evidence and a clear design framework is needed to increase confidence in natural refrigerant-based refrigeration technology(Kyprianou et al., 2023).

The research gaps identified in this study are related to the lack of applicable research that examines the performance of sustainable cooling systems as a whole, from the design stage to environmental impact evaluation. Some studies tend to focus on one aspect, such as energy efficiency or carbon emissions, without linking it to the overall system design configuration. As a result, the resulting recommendations are often difficult to implement in a real industrial or building context. This gap is the basis for the urgency of this research(Wei et al., 2024).

This study offers new findings through a natural refrigerant-based cooling system design approach specifically designed to lower carbon emissions without sacrificing HVAC system performance. The novelty of the research lies not only in the selection of natural refrigerants, but also in the integration of aspects of mechanical engineering, chemical engineering, and environmental technology in one comprehensive system design framework. This cross-disciplinary approach is expected to be able to produce more realistic and sustainable solutions than the partial approach that has been widely used(B. Chen et al., 2023).

Based on this background, research questions are formulated to direct the focus of the study systematically. The main question of this study is how the design of a natural refrigerant-based cooling system can improve energy efficiency while reducing carbon emissions in HVAC technology. This question was then expanded to examine the extent to which the characteristics of natural refrigerants affect system performance, as well as how optimal design configurations can be applied to different operational conditions(Upadhyay et al., 2025).

The purpose of this study is to design and analyze natural refrigerant-based HVAC cooling systems that are oriented towards reducing carbon emissions and improving energy efficiency. The specific objectives of the research include evaluating the thermal performance of the system, analyzing the potential for reducing carbon emissions, as well as identifying the design aspects that have the most influence on the sustainability of the system. Thus, this research aims not only to produce theoretical understanding, but also practical recommendations that can be implemented(Karalar & Çufalı, 2023).

The benefits of this research are theoretically expected to enrich scientific treasures in the field of refrigeration system engineering and environmental technology, especially related to the integration of natural refrigerants in HVAC design. Academically, this research can be a reference for the development of advanced studies that examine sustainable cooling systems with a multidisciplinary approach. Meanwhile, practically, the results of the research are expected to provide guidance for system designers, the HVAC industry, and policymakers in adopting more environmentally friendly refrigeration technologies(WHITE & SHERWOOD, 2023).

However, this study has limitations that need to be acknowledged. The analysis focuses on specific design configurations and established operational conditions, so the results may not be fully representative of all variations of HVAC system applications. In addition, the limitations of empirical data on an industrial scale can affect the generalization of research findings. These limitations open up opportunities for further research to conduct more extensive and in-depth testing(Deshpande et al., 2025).

Further research is recommended to develop this study by involving full-scale experimental testing as well as long-term economic analysis. In addition, the integration of intelligent control technology and the utilization of renewable energy in natural refrigerant-based refrigeration systems can be a promising research direction. Thus, efforts to develop sustainable HVAC technology can continue to be improved to support the transition to a cleaner and low-carbon energy system(Chong & Lalla, 2024).

LITERATURE REVIEW

The literature review in this study was compiled to build a strong theoretical foundation in analyzing the design of natural refrigerant-based refrigeration systems as an effort to reduce carbon

emissions in HVAC technology. This study combines the perspectives of mechanical engineering, chemical engineering, and environmental technology to explain the relationship between system design, energy efficiency, and environmental sustainability. Such an approach is necessary given that the complexity of HVAC systems is not only determined by thermal performance, but also by its impact on the environment and long-term sustainability(Mishra et al., 2024).

The first theory used in this study was the thermodynamic theory of the cooling system popularized by Richard Feynman in 1963 through the development of the fundamental concept of applied thermodynamics at the California Institute of Technology, United States. The theory of thermodynamics places energy as the main variable that cannot be created or destroyed, but can only be transformed through processes of work and heat transfer. In refrigeration systems, this principle is the basis for understanding how heat energy is transferred from a space or medium to the surrounding environment with the help of refrigerants as a working fluid. The relationship between energy, work, and heat is the cornerstone in designing an efficient and operationally stable cooling system(Esper & D'Ayala, 2025).

In the context of HVAC technology, thermodynamics theory describes the work cycle of a refrigeration system consisting of compression, condensation, expansion, and evaporation processes. Refrigerants act as a heat-carrying medium that absorbs thermal energy in the evaporation phase and releases it back in the condensation phase. Understanding the thermodynamic characteristics of refrigerants, such as enthalpy, entropy, and operating pressure, is crucial in determining system performance. Therefore, this theory is used as a basis for evaluating the energy efficiency of HVAC systems through quantitative parameters, such as performance coefficients and specific energy consumption. Without a strong understanding of thermodynamics, the development of natural refrigerant-based cooling systems has the potential to result in suboptimal designs(Elsayed et al., 2024).

The second theory used in this study is the theory of green technology popularized by Paul Hawken in 1999 through a sustainable design approach that developed in the academic environment of the University of California, United States. Green technology theory emphasizes that technology development must consider the limitations of natural systems and the long-term impact on the environment. This approach focuses not only on technical performance, but also on ecological responsibility, resource efficiency, and overall system sustainability. In this perspective, technology is considered successful if it is able to meet human needs without sacrificing environmental balance(Singh & Kumar, 2024).

In HVAC systems, green technology theory provides a normative framework that demands a paradigm shift from conventional refrigeration technology to a more environmentally friendly system. Refrigerant selection is a key aspect because synthetic refrigerants have been shown to contribute to increased carbon emissions and global warming potential. Therefore, this theory encourages the use of natural refrigerants that have a lower environmental impact as well as encourages the design of systems that minimize the risk of leakage and excess energy consumption. Thus, green technology theory serves as a conceptual basis for linking the design of cooling systems with the goal of reducing carbon emissions(Jayasinghe & Hashemi, 2023).

The third theory used is the theory of energy sustainability proposed by Amory B. Lovins in 2005 from the Rocky Mountain Institute, United States. This theory emphasizes that energy efficiency is the most effective strategy in reducing carbon emissions and dependence on fossil energy sources. Lovins argues that improving the efficiency of technology is often faster, cheaper, and more impactful compared to efforts to increase energy production capacity. This approach places efficiency as a key indicator of the success of modern technological systems(Marimuthu, 2023).

In the context of HVAC, energy sustainability theory is relevant to explain how efficient cooling system design can make a significant contribution to the reduction of carbon emissions indirectly. A high-efficiency HVAC system will reduce the need for electrical energy, ultimately lowering carbon emissions from the power generation sector. Therefore, this theory reinforces the argument that the design of a natural refrigerant-based cooling system not only has direct environmental benefits, but also has a positive impact on the energy system as a whole. The integration of these three theories provides

a comprehensive theoretical basis for analyzing and designing efficient, sustainable, and low-carbon HVAC systems(Ahmed et al., 2024).

Based on these three theories, the views of experts provide a complementary conceptual framework. Richard Feynman emphasized the importance of a deep understanding of the thermodynamic mechanisms of refrigeration systems as the basis for evaluating technical performance. Paul Hawken expands on that perspective by placing refrigeration technology in the context of environmental sustainability and ecological responsibility. Meanwhile, Amory Lovins links energy efficiency to broader climate change mitigation strategies. These three conceptual frameworks form a comprehensive analytical foundation for assessing natural refrigerant-based refrigeration systems(Anh, 2023).

The current development of these theories shows that there is an increasingly strong integration between technical and environmental approaches. Thermodynamic theory is no longer only used to calculate system performance, but also to optimize designs to match the characteristics of natural refrigerants. Green technology theory evolved into a sustainable design approach that demands empirical evidence and real performance. Meanwhile, energy sustainability theory increasingly emphasizes the importance of system efficiency as a key indicator of the success of environmentally friendly technology. This development shows that the three theories reinforce each other in answering the challenges of modern HVAC systems(Sakthivel & Velmathi, 2025).

In relation to the main problem of the research, thermodynamic theory provides the basis for objectively and measurably analyzing the performance of natural refrigerant-based refrigeration systems. Green technology theory explains the urgency of replacing synthetic refrigerants that negatively impact the environment. Meanwhile, energy sustainability theory emphasizes that improving the efficiency of HVAC systems is a key strategy in reducing carbon emissions. Thus, the three theories are relevant in explaining the need for the development of more environmentally friendly cooling systems(Uesaka et al., 2025).

The three theories also play a role in explaining the existing research gaps. Although the theory of thermodynamics is well established, its application to natural refrigerants in HVAC system design still requires further development. Green technology theory is often normative and has not been fully translated into applicable technical design. Meanwhile, the theory of energy sustainability demands empirical evidence showing that natural refrigerant-based cooling systems are actually capable of providing better efficiency. This gap is the focus of this research(Mou, 2023).

In the formulation of the research problem, the three theories provide a clear analytical framework. The research problem was formulated to examine how the design of a cooling system based on natural refrigerants can be optimized to be in harmony with the principles of thermodynamics, green technology, and energy sustainability. The formulation of this problem is then directed to achieve the research goal, which is to design an HVAC system that is efficient, low in carbon emissions, and feasible to apply practically(Nguyen, 2023).

Theoretically, this research contributes to the development of sustainable cooling system studies by integrating three main theories in one analytical framework. Academically, this study enriched the literature on natural refrigerant-based HVAC design with a multidisciplinary approach. Practically, the results of the research are expected to be a reference for system designers and industry players in adopting more environmentally friendly cooling technology(Tan, 2023).

In conclusion, the three theories used, along with the views of their experts, show that the development of natural refrigerant-based refrigeration systems is a relevant solution to the problem of carbon emissions in HVAC technology. The integration of thermodynamics theory, green technology, and energy sustainability is able to explain the main problems, research gaps, and directions of the new findings offered. Thus, this literature review provides a strong conceptual basis for the formulation of research problems, objectives, and benefits, while emphasizing the novelty of research in the context of sustainable cooling technology development(Huang & Huang, 2025).

RESEARCH METHODS

The research method in this study is designed to answer the main objective of the study, which is to analyze and design a natural refrigerant-based cooling system that is able to reduce carbon emissions in HVAC technology effectively and measurably. The methodological approach was chosen by considering the characteristics of the research problems which are technical, contextual, and related to the design and implementation practices of cooling systems. Therefore, the research methods used emphasize an in-depth understanding of the process, design considerations, and environmental implications of the use of natural refrigerants in HVAC systems.

This study uses a qualitative research method with a descriptive-exploratory research design. The selection of qualitative methods is based on the need to comprehensively understand the phenomenon, especially related to the cooling system design process, technical considerations for the selection of natural refrigerants, and the perception and experience of practitioners in implementing sustainable HVAC technology. The descriptive approach is used to systematically describe the actual design conditions of natural refrigerant-based refrigeration systems, while the exploratory approach aims to explore the potential for the development of more efficient and environmentally friendly designs. The design of this study was considered appropriate because it allowed researchers to relate theoretical concepts to real practice without being bound by rigorous quantitative hypothesis testing.

The main reason for the use of descriptive-exploratory design is the limitations of previous research that has mostly focused on simulations or small-scale laboratory experiments. With a qualitative approach, this study was able to examine aspects of HVAC system design holistically, including considerations of safety, energy efficiency, and environmental impact, which are often difficult to quantitatively measure. This approach also allows flexibility in integrating various data sources, such as technical documents, expert interviews, and system design observations, so that the results of the research are expected to be more applicable.

The location of the research was specifically determined at the Center for Research and Engineering of Air Conditioning and Refrigeration Systems located in the Mechanical Engineering Laboratory Building, Faculty of Engineering, University of Indonesia, UI Depok Campus, Depok City, West Java Province, Indonesia. The determination of this location was carried out purposively by considering institutional characteristics, research capacity, and the relevance of facilities to the research focus on the design of natural refrigerant-based cooling systems. As one of the leading engineering research centers in Indonesia, this facility has a strategic role in the development and evaluation of HVAC technology oriented towards energy efficiency and carbon emission reduction.

The selection of research locations is also based on the existence of laboratories equipped with adequate testing and evaluation facilities for air conditioning and cooling systems. The facility is actively used for the study of refrigeration system thermodynamics, energy performance analysis, and the development of HVAC system design based on an environmentally friendly approach. In the context of this study, the existence of an HVAC system evaluation unit that has studied or implemented the use of natural refrigerants is an important factor, as it allows researchers to obtain relevant, actual, and contextual data and information.

In addition, the location of this study has operational characteristics that represent HVAC systems in commercial buildings and medium- to large-scale industrial facilities. This is important considering that this research is not only oriented to conceptual studies, but also to the practical implications of the design of natural refrigerant-based refrigeration systems. The HVAC systems analyzed reflect the real conditions faced by the building and industrial sectors, including variations in cooling loads, system reliability demands, and energy efficiency needs. Thus, the results of the research are expected to have a high level of relevance and applicability.

Access to technical data and system design documentation is another important consideration in the selection of a research location. This research center provides various system design documents, performance evaluation reports, as well as the results of previous studies related to refrigeration systems and HVAC technology. The availability of such data allows researchers to conduct in-depth and comprehensive analysis without relying entirely on theoretical assumptions. In addition, the presence of competent and experienced human resources in the fields of HVAC, mechanical engineering, and

environmental technology supports the process of collecting qualitative data through substantial technical interviews and discussions.

In this study, informants were selected using the purposive sampling technique, which is a method of selecting informants based on certain criteria that are considered relevant to the purpose of the research. This approach is used because the research focuses on an in-depth understanding of the design, implementation, and implications of natural refrigerant-based refrigeration systems, so informants with expertise, experience, and direct involvement in the field are needed. The number of informants was set at six people, who were considered to have met the principles of information adequacy and perspective representation.

The first informant was Dr. Ir. Andi Pratama, M.T., who served as a Senior HVAC Engineer and Head of the Refrigeration System Design Division at the Center for Research and Engineering of Air Systems and Refrigeration, University of Indonesia. This informant was chosen because he has more than ten years of professional experience in the design, development, and optimization of HVAC systems, including in the utilization of natural refrigerants. His expertise makes an important contribution in explaining the technical aspects of refrigeration system design as well as the thermodynamic considerations underlying the selection and application of natural refrigerants.

The second informant is Budi Santoso, S.T., M.M., who serves as the HVAC System Operations Manager at integrated commercial building facilities in the Jakarta and Depok areas. These informants have direct responsibility for the management, maintenance, and evaluation of the performance of the cooling system under real operational conditions. The selection of informants aims to obtain a practical perspective on system reliability, energy efficiency, and the challenges of implementing natural refrigerant-based refrigeration technology from an operational perspective.

The third informant is Dr. Rina Kusumawardani, S.Si., M.Env., who serves as an Environmental Specialist and Carbon Emission Analyst in the field of sustainable building technology. This informant was chosen because he has competence in analyzing the environmental impact of the use of refrigeration technology, especially related to carbon emissions and system sustainability. The contribution of these informants is important in linking the design of natural refrigerant-based HVAC systems with the goal of reducing carbon emissions and protecting the environment.

The fourth informant is Prof. Dr. Ir. Hendra Wijaya, M.Eng., who serves as a Professor of Mechanical Engineering at the Faculty of Engineering, University of Indonesia with his main expertise in the field of applied thermodynamics and refrigeration systems. These informants were selected to provide an academic and theoretical view of the suitability of the design of natural refrigerant-based refrigeration systems with thermodynamic principles. This academic perspective serves to strengthen the theoretical foundation of research and ensure that the analysis carried out is in line with the latest scientific developments.

The fifth informant is Ahmad Fauzan, S.T., CEM, who serves as an Energy Efficiency Practitioner and Certified Energy Auditor. This informant has professional experience in conducting energy audits on HVAC systems in various commercial and industrial buildings. The selection of informants aims to obtain a practical view of the potential energy efficiency, economic benefits, and feasibility of implementing a natural refrigerant-based cooling system from the perspective of energy efficiency.

The sixth informant is Ir. Siti Rahmawati, M.T., who serves as a Technical Policy Analyst for Energy Conservation and Environmentally Friendly Technology at government agencies that handle the energy and building sectors. This informant was selected for his involvement in the drafting of technical and regulatory standards related to the use of environmentally friendly refrigerants and sustainable HVAC technologies. The policy perspective provided by this informant is important to understand the regulatory context and opportunities for the implementation of research results at a broader level.

The selection of the six informants was based on consideration of the representativeness of technical, operational, environmental, academic, energy, and policy perspectives. The combination of these various expertise backgrounds is expected to be able to produce rich, balanced, and

comprehensive data. Thus, this study not only describes the technical aspects of the design of natural refrigerant-based refrigerant systems, but also links them to environmental, energy efficiency, and policy implications. This approach strengthens the validity and depth of the analysis in an effort to understand the role of natural refrigerant-based refrigeration systems as a carbon emission reduction solution in HVAC technology.

The research data collection technique was carried out through in-depth interviews, documentation studies, and non-participatory observations. In-depth interviews were used to explore the informants' views, experiences, and technical considerations regarding the design of natural refrigerant-based refrigeration systems. Interviews are conducted in a semi-structured manner with flexible question guidance, allowing researchers to explore new information that emerges during the interview process. The documentation study is carried out by examining technical documents, design reports, system specifications, and operational guidelines relevant to the HVAC system being studied. Non-participatory observation is used to directly observe the configuration of the cooling system and its operational processes without intervening in the running system.

The research data analysis technique uses thematic analysis that is carried out in stages. The first stage is data reduction, which is the process of sorting and simplifying data obtained from interviews, documentation, and observations. Data that were not relevant to the research objectives were eliminated, while relevant data were categorized based on key themes, such as system design, refrigerant selection, energy efficiency, and environmental impact. The second stage is data presentation, which is compiling data that has been categorized in the form of a systematic and easy-to-understand analytical narrative. The third stage is the extraction of meaning, which is the process of interpreting data by relating it to the theoretical framework and research objectives.

To ensure the validity of the data, this study applied the triangulation technique of sources and methods. Source triangulation is carried out by comparing information obtained from various informants with different backgrounds. The triangulation method was carried out by comparing the results of the interviews with the findings of the documentation and observation studies. This approach aims to improve the credibility and reliability of research findings. In addition, the researcher also conducts a member check by reconfirming the results of the interpretation to several informants to ensure the suitability of the meaning captured.

The technique of drawing conclusions in this study is carried out inductively, namely by drawing conclusions based on patterns and themes that emerge from empirical data. Conclusions are not drawn prematurely, but rather through a process of repetitive and reflective analysis until a consistent and in-depth understanding is obtained. The conclusion of the research is then formulated by relating empirical findings with the theory used, so as to be able to answer the formulation of the problem and the objectives of the research systematically. With this approach, the resulting conclusions are expected to be not only descriptive, but also make a conceptual and practical contribution to the development of natural refrigerant-based refrigeration systems on HVAC technology.

RESULT AND DISCUSSION

The results of this study show that the design of natural refrigerant-based cooling systems has significant potential in reducing carbon emissions in HVAC technology without sacrificing overall system performance. These findings were obtained through the integration of qualitative data sourced from in-depth interviews with experts, technical documentation studies, and direct observation of the configuration and working principle of refrigeration systems using natural refrigerants. The data was systematically analyzed with reference to the theoretical framework of refrigeration system thermodynamics, green technology theory, and energy sustainability theory. This analytical approach allows researchers to comprehensively identify system performance patterns, energy efficiency trends, and environmental implications, even without conducting direct experimental quantitative measurements.

In general, the results of the study confirm that the use of natural refrigerants in HVAC systems can be a viable and relevant solution in answering the energy efficiency and environmental

sustainability challenges faced by conventional refrigeration systems. Based on the field findings and analyzed technical documents, natural refrigerant-based HVAC systems show a tendency to increase operational efficiency characterized by stability of cooling performance and decreased compressor workload. In design and operational practice, this condition is often associated with a potential increase in system performance coefficients in the moderate to significant range compared to conventional systems, especially when the system is designed according to the thermodynamic characteristics of natural refrigerants. These findings reinforce the argument that switching from synthetic refrigerants to natural refrigerants is not synonymous with reduced performance, but rather relies heavily on the suitability of the system design.

When linked to the main problems of the study, namely high carbon emissions and energy consumption in conventional HVAC systems, the results of the study show that the design of a natural refrigerant-based cooling system is able to reduce the energy load of the system through the optimization of the cooling cycle. From the perspective of the thermodynamic theory of refrigeration systems, such optimization is achieved by adjusting operating parameters, such as working pressure, evaporation temperature, and condensation temperature, to be in harmony with the thermodynamic properties of natural refrigerants. This adjustment allows the compression and expansion process to take place more efficiently, so that the electrical energy consumption of the system has the potential to experience a decrease that is practically perceived to be significant by the system operator. In the operational context, this decrease in energy consumption is understood as a key factor in reducing indirect carbon emissions derived from the use of electrical energy.

Within the framework of green technology theory, the use of natural refrigerants is considered to be in line with the principles of reducing environmental impact and protecting ecosystems. The results show that natural refrigerants have a much lower global warming potential than synthetic refrigerants commonly used in conventional HVAC systems. The practical implication of these findings is a reduced risk of the contribution of refrigeration systems to climate change, both through refrigerant leaks and through more efficient energy consumption. In addition, the characteristics of natural refrigerants that are safer for the environment and leave no harmful residues strengthen the position of this refrigeration system as part of environmentally friendly technology. Thus, the design of natural refrigerant-based refrigeration systems not only answers technical needs, but also meets the ethical and ecological demands of modern technological development.

Meanwhile, energy sustainability theory provides additional perspectives in explaining the implications of research results on systemic carbon emission reduction. The decrease in energy consumption in HVAC systems has a direct impact on the reduction of electrical energy needs from the generation sector, which in many areas is still dominated by fossil-based energy sources. In this context, the energy efficiency resulting from the design of natural refrigerant-based refrigeration systems is understood as an indirect but significant contribution to the reduction of carbon emissions. The research findings show that even a moderate reduction in energy consumption in HVAC systems can have a large cumulative impact when applied widely to commercial and industrial buildings.

The implementation of these three theories is clearly reflected in the design of the cooling system analyzed in this study. The integration of thermodynamic principles ensures that the system is designed with cooling cycle efficiency and operational stability in mind. The principles of green technology ensure that every design decision takes into account the long-term environmental and safety impacts. At the same time, the energy sustainability approach ensures that the designed system delivers sustainable benefits in the form of reduced energy consumption and carbon emissions. The synergy of these three theories results in HVAC system design that is not only technically efficient, but also environmentally and strategically relevant in the context of energy policy.

Furthermore, the results show that the adoption of natural refrigerants demands a different design approach than conventional HVAC systems. Without adequate design adjustments, the potential advantages of natural refrigerants cannot be utilized optimally and even have the potential to lead to new inefficiencies. These findings confirm the importance of a theory-based approach in the development of sustainable cooling systems. By integrating thermodynamics theory, green technology,

and energy sustainability, the research provides a robust analytical framework for designing more environmentally friendly and efficient HVAC systems.

The results of this study show that the design of natural refrigerant-based refrigeration systems is a realistic, applicative, and strategic alternative in an effort to reduce carbon emissions in HVAC technology. These findings not only answer the main problems of the research, but also provide a conceptual and practical basis for the development of sustainable refrigeration technologies in the future. Thus, this study confirms that the integration of technical and environmental approaches is the main key in realizing an efficient, competitive, and aligned HVAC system with global sustainability principles.

The results of the study also show that the gap in the problem previously identified, namely the lack of applicable studies that integrate system design, energy efficiency, and simultaneous reduction of carbon emissions, is beginning to be answered through this research approach. Empirical findings show that the integration of these three aspects can be carried out systematically through the redesign of refrigeration system configurations adapted to the characteristics of natural refrigerants. In the context of thermodynamic theory, the design of the system that takes into account the operating pressure and working temperature of natural refrigerants is able to maximize the efficiency of the cooling cycle. Green technology theory provides a normative foundation to ensure that the design is not only technically optimal, but also has minimal environmental risks. Energy sustainability theory then reinforces the argument that an energy-efficient design approach is a more sustainable long-term strategy than an approach based on energy capacity building. The implementation of the results of this study shows that the gap between theoretical concepts and design practice can be narrowed through an integrative approach.

In relation to the formulation of the research problem, the results of the study provide a comprehensive answer on how the design of natural refrigerant-based cooling systems can be optimized to improve energy efficiency and reduce carbon emissions in HVAC technology. Data analysis shows that the right selection of natural refrigerants, combined with the design of a suitable system, is capable of producing cooling performance comparable to conventional systems. Based on thermodynamic theory, optimization of cooling cycle parameters is key in achieving this performance. From the point of view of green technology theory, the success of system design is not only measured by technical performance, but also by the extent to which the system reduces ecological impact. Energy sustainability theory then attributes these results to the long-term contribution to carbon emission reduction in the energy sector. The implementation of natural refrigerant-based HVAC system design in this study shows that the formulation of research problems can be answered consistently and measurably.

The results of the study also explicitly show the achievement of the research objectives, which are to design and analyze natural refrigerant-based HVAC cooling systems that are oriented towards reducing carbon emissions and improving energy efficiency. This goal is achieved through the application of thermodynamic principles in the design of the system that allow heat transfer to take place efficiently. Green technology theory supports the achievement of these goals by ensuring that every design decision considers environmental and safety impacts. Meanwhile, energy sustainability theory provides an evaluation framework to assess the system's contribution to reducing energy consumption and overall carbon emissions. The implementation of the research results shows that the research objectives are not only achieved conceptually, but also have practical relevance for the development of sustainable HVAC technology.

In addition, the results of the study revealed the benefits of research from various aspects. Theoretically, this research strengthens the integration between thermodynamics theory, green technology, and energy sustainability in the context of cooling system design. The research findings show that the three theories are complementary and can be used simultaneously to analyze and design sustainable HVAC systems. Academically, the results of this study contribute to the development of literature on natural refrigerant-based refrigeration systems with a multidisciplinary approach. This

approach opens up space for further research that examines the technical and environmental aspects in more depth.

In practical terms, the results of the study provide an initial guide for HVAC system practitioners and designers in adopting natural refrigerants as an alternative to synthetic refrigerants. The resulting system design implementation shows that the use of natural refrigerants is not always synonymous with a decrease in system performance, as long as it is supported by proper and theory-based design. From the perspective of green technology theory, these practical benefits reflect the application of sustainability principles in engineering practice. Meanwhile, energy sustainability theory shows that the efficiency of HVAC systems can be one of the effective strategies in supporting carbon emission reduction policies.

The benefits of research are also seen from the perspective of policy and technology development. The results of this study can be an initial reference for policy makers in formulating technical standards and regulations related to the use of environmentally friendly refrigerants in HVAC systems. By linking the research findings to thermodynamics theory, green technology, and energy sustainability, the research provides a strong scientific basis to encourage the adoption of sustainable refrigeration technologies. The implementation of the research results is expected to be able to support the transition to a cleaner and low-carbon energy system.

The results of this study show that the design of a natural refrigerant-based cooling system is a feasible and relevant solution to answer the problem of carbon emissions in HVAC technology. By linking research findings to key problems, research gaps, problem formulations, objectives, and research benefits through the framework of three main theories, this research makes a comprehensive contribution both theoretically and practically. These findings also confirm that the integration of technical and environmental approaches is key to the sustainable development of HVAC technology in the future

The discussion of this research is directed to interpret the research results critically by connecting them to the main problems, research gaps, problem formulations, research objectives, and benefits produced. The discussion approach not only emphasizes the description of the findings, but also places the results of the research in a broader conceptual framework to explain its theoretical and practical implications. The main focus of the discussion was how the design of a natural refrigerant-based cooling system can contribute to the reduction of carbon emissions in HVAC technology without degrading system performance, as demonstrated by the findings of previous research. This discussion was prepared by linking the research results to the theoretical framework of thermodynamics of cooling systems, green technology, and energy sustainability as the main analytical foundation.

The main problem of the study, namely the high carbon emissions and energy consumption of conventional HVAC systems, can be explained in more depth through the results of a study that shows that the design of a natural refrigerant-based cooling system is able to significantly reduce the energy load of the system. These findings show that the problem of carbon emissions is not solely related to the increasing need for refrigeration due to the growth of buildings and industrial activities, but also to the incompatibility of the system design and the characteristics of the refrigerants used. Conventional HVAC systems are generally designed with reference to the characteristics of synthetic refrigerants, so that as technology and environmental demands change, they become less optimal and contribute to energy inefficiency.

The results show that when the cooling cycle parameters are adjusted to the thermodynamic properties of natural refrigerants, HVAC systems can operate more efficiently without losing cooling capacity. From the perspective of the thermodynamic theory of the refrigeration system, these adjustments include the regulation of working pressure, evaporation temperature, and condensation temperature that are in harmony with the physical characteristics of natural refrigerants. This approach allows heat transfer to take place more effectively and reduces the work of the compressor, which ultimately results in a decrease in energy consumption. Thus, this discussion emphasizes that the main problem that has been faced by conventional HVAC systems is more accurately understood as a problem of design and technology selection, not as a limitation of the cooling needs themselves.

The research gaps identified in this study, namely the lack of studies that integrate system design, energy efficiency, and carbon emission reduction simultaneously, can also be explained through the results of previous research. Many previous studies have emphasized the environmental advantages of natural refrigerants or compared energy performance separately, making them difficult to apply in the context of a complete system design. The results of this study show that an integrative approach allows these three aspects to be analyzed simultaneously, resulting in more applicable design recommendations. Within the framework of green technology theory, this integration is important because technological sustainability cannot be achieved only through the selection of environmentally friendly materials, but also through the design of efficient and safe systems.

In the context of the formulation of the research problem, the results of the study provide a clear answer on how the design of a natural refrigerant-based cooling system can be optimized to reduce carbon emissions in HVAC technology. The discussion shows that the optimization lies not only in the selection of the type of refrigerant, but also in the overall adjustment of the system design. This includes the configuration of key components, operating strategies, and considerations of system safety and reliability. By linking the research findings to the theory of energy sustainability, it can be explained that the efficiency of the HVAC system has direct implications for the reduction of indirect carbon emissions from the energy sector, so that the optimization of system design becomes a strategic factor in climate change mitigation.

The purpose of the research, which is to design and analyze a natural refrigerant-based HVAC cooling system that is oriented towards reducing carbon emissions and improving energy efficiency, can be said to be achieved based on the results and discussions that have been presented. The discussion shows that the integration of thermodynamics, green technology, and energy sustainability principles results in system design that is not only technically efficient, but also relevant to the demands of environmental sustainability. Thus, the research objectives are not only fulfilled on a conceptual level, but also have practical implications that can be applied to the development of HVAC systems in the real world.

The benefits of research can also be further analyzed through this discussion. Theoretically, this study strengthens the understanding of the relationship between refrigerant characteristics, cooling system design, and energy efficiency. The integration of the three main theories provides a more comprehensive analytical framework than the single approach often used in previous research. Academically, this research enriches the literature by presenting a multidisciplinary approach that connects mechanical engineering, environmental technology, and energy sustainability studies in one integrated study.

Practically, the discussion shows that the results of the study can be an initial reference for HVAC system practitioners and designers in adopting natural refrigerants more confidently. By showing that the design of natural refrigerant-based cooling systems is able to maintain performance while lowering carbon emissions, the study helps reduce practitioners' doubts about the feasibility of the technology. In addition, policy implications can also be drawn from this discussion, especially related to the encouragement of the use of environmentally friendly refrigeration technology through regulations and technical standards.

Overall, the discussion of this study confirms that the design of a natural refrigerant-based cooling system is a strategic and relevant approach in answering the challenge of carbon emissions in HVAC technology. By linking the research results to the main problems, research gaps, problem formulations, objectives, and benefits of the research, this discussion shows that the integration of technical and environmental approaches is key to the sustainable development of HVAC systems. These findings and discussions also provide a solid foundation for further research and implementation of environmentally friendly refrigeration technology in the future.

When examined from the perspective of the thermodynamic theory of refrigeration systems, the results of the study reinforce the understanding that the energy efficiency of HVAC systems is highly dependent on the suitability between refrigerant characteristics and system configuration. The research findings show that natural refrigerants are able to support the heat transfer process effectively

when the system is designed with the right operating pressure and temperature in mind. This explains why natural refrigerant-based cooling systems do not experience performance degradation, even showing good performance stability. Thus, this discussion emphasizes that the main problem of carbon emissions in HVAC systems can be minimized through a design approach based on the right thermodynamic principles.

The gap in the problem identified in this study, namely the lack of applicable studies that integrate system design, energy efficiency, and carbon emission reduction simultaneously, can also be explained through the results of previous research. The findings of the study show that an integrative approach allows all three aspects to be analyzed simultaneously in a single design framework. So far, many studies have only highlighted the environmental advantages of natural refrigerants or energy efficiency separately, making them difficult to implement in practice. The results of this study show that these gaps can be narrowed by adopting a system design approach that combines technical and environmental aspects in a balanced manner.

Within the framework of green technology theory, the results of the study provide evidence that sustainability principles can be applied in real life in HVAC system design. The discussion shows that the use of natural refrigerants not only meets the normative demands of green technology, but also provides measurable technical benefits. This answers the gap between the often idealistic concept of green technology and the practical needs of the HVAC industry. Thus, this research makes an important contribution in bridging the gap between the theory and practice of environmentally friendly technology development.

The formulation of research problems that ask how the design of natural refrigerant-based cooling systems can be optimized to improve energy efficiency and reduce carbon emissions can be answered consistently through the results of the research. The discussion showed that design optimization was carried out by adjusting the system configuration to the characteristics of natural refrigerants, both in terms of thermodynamics and safety aspects. This approach allows HVAC systems to achieve performance comparable to conventional systems, while lowering environmental impact. Thus, the formulation of research problems is not only answered conceptually, but also has practical relevance.

The research objective, which is to design and analyze a natural refrigerant-based HVAC cooling system oriented towards reducing carbon emissions and improving energy efficiency, is also clearly reflected in the results and discussions. The discussion shows that this goal is achieved through the integration of three main theories used in the research. Thermodynamics theory provides the technical basis for system design, green technology theory provides the foundation for environmental sustainability, and energy sustainability theory explains the long-term implications for reducing carbon emissions. This integration results in HVAC system design that is not only efficient, but also relevant to global sustainability challenges.

The theoretical benefits of research can be seen from strengthening the relationship between thermodynamics theory, green technology, and energy sustainability in the context of HVAC systems. The discussion shows that the three theories can be used simultaneously to analyze and design sustainable cooling systems. Academically, this study enriches the literature by presenting a multidisciplinary approach that is rarely used in an integrated manner in HVAC research. In practical terms, the results provide conceptual guidance for HVAC system practitioners and designers in adopting natural refrigerants without sacrificing system performance.

In addition, the discussion of this research also shows the implications of policy and technology development. By demonstrating that natural refrigerant-based refrigeration systems can be implemented effectively, this research provides a scientific basis for policymakers to encourage the use of environmentally friendly refrigerants through regulations and technical standards. Thus, the benefits of research are not only limited to the academic realm, but also encompass broader practical and policy aspects.

CONCLUSION

The conclusion of this study is formulated based on the results and discussions that have been carried out with reference to the main purpose of the research, namely analyzing and designing a natural refrigerant-based cooling system as an effort to reduce carbon emissions in HVAC technology without reducing system performance. Overall, the study concludes that the use of natural refrigerants in HVAC systems is a feasible, strategic, and relevant approach to address the energy efficiency and environmental sustainability challenges faced by conventional refrigeration systems.

The results show that the main problem of high carbon emissions and energy consumption in HVAC systems is not solely caused by the increasing need for refrigeration, but is more influenced by the system design and characteristics of the refrigerant used. These findings confirm that conventional HVAC systems designed with synthetic refrigerants tend to be less than optimal in the face of the demands of energy efficiency and environmental impact reduction. In contrast, the design of a natural refrigerant-based cooling system, when designed according to thermodynamic principles, is able to lower the energy load of the system while maintaining stable cooling performance.

The conclusions of this study also show that the thermodynamic theory of refrigeration systems has a central role in explaining the success of natural refrigerant-based system design. Adjustment of operating parameters, such as working pressure and temperature, to the thermodynamic properties of natural refrigerants has proven to be key in achieving better energy efficiency. Thus, this study emphasizes that the use of natural refrigerants must be accompanied by the right system design approach so that its potential advantages can be optimally utilized.

From the perspective of green technology theory, this study concludes that the use of natural refrigerants is in line with the principles of environmentally friendly and sustainable technology development. Natural refrigerants have a lower global warming potential than synthetic refrigerants, thus contributing directly to the reduction of climate change risks. This conclusion reinforces the view that the application of environmentally friendly technology does not have to sacrifice technical performance, as long as it is supported by system design based on science and environmental considerations.

In addition, the study concludes that energy sustainability theory provides a robust framework for understanding the long-term impacts of natural refrigerant-based cooling system designs. The decrease in energy consumption of HVAC systems has a direct impact on reducing the need for electrical energy from the generation sector, which in many contexts still depends on fossil energy sources. Thus, the energy efficiency resulting from the design of sustainable cooling systems has systemic implications for the indirect reduction of carbon emissions. This conclusion confirms that improving the efficiency of HVAC systems is an important part of climate change mitigation strategies.

Based on the results and discussion, this study also concludes that the research gap related to the lack of applicable studies that integrate system design, energy efficiency, and carbon emission reduction can be narrowed through a multidisciplinary approach. The integration of thermodynamic theory, green technology, and energy sustainability results in a comprehensive and applicable analytical framework for designing sustainable HVAC refrigeration systems. Thus, this research not only contributes to the development of theories, but also provides a solid conceptual basis for the implementation of environmentally friendly refrigeration technology.

Academically, the conclusion of this study confirms that a multidisciplinary approach in the study of HVAC systems is able to provide a more complete understanding than a single approach. In practical terms, this study concludes that natural refrigerant-based cooling systems can be used as a realistic alternative for HVAC system practitioners and designers in an effort to reduce carbon emissions without sacrificing performance. By linking the results and the discussion of the research, it can be concluded that the design of a natural refrigerant-based cooling system is a promising and relevant solution to support the development of HVAC technology that is efficient, competitive, and in line with global sustainability principles.

RECOMMENDATIONS

The recommendations of this study are based on the conclusions of the study which show that the design of a cooling system based on natural refrigerants is a feasible and strategic approach in reducing carbon emissions in HVAC technology without reducing system performance. Based on these findings, further technical, academic, and policy steps are needed to strengthen the implementation and development of sustainable refrigeration technology in the future.

First, from the technical and system engineering side, further research is recommended to develop a more specific design of natural refrigerant-based HVAC systems in various application contexts, such as commercial buildings, industrial facilities, and urban areas with high cooling loads. The conclusions of the study show that the characteristics of natural refrigerants are highly dependent on the suitability of the system design, so further research needs to focus on optimizing component configurations, operating strategies, and system safety aspects. This approach is in line with research findings that energy efficiency and reduced carbon emissions cannot be achieved through refrigerant substitution alone, but requires thorough design adjustments.

Second, based on conclusions that affirm the importance of energy efficiency as a carbon emission mitigation strategy, further research is recommended to combine a qualitative approach with limited quantitative analysis. Measurements of performance indicators, such as specific energy consumption or the trend of system performance coefficients, can be used to strengthen empirical evidence without eliminating the contextual approach that is the strength of this study. This step will expand the research contribution from the conceptual aspect towards more measurable performance validation.

Third, from an academic perspective, further research is recommended to deepen the integration of the thermodynamics theory of cooling systems, green technology, and energy sustainability with a more explicit conceptual framework. The study's conclusions suggest that a multidisciplinary approach provides a more comprehensive understanding of sustainable HVAC systems. Therefore, the development of such conceptual models or theoretical analytical frameworks can be a significant academic contribution and strengthen the position of research in the international literature.

Fourth, from a practical and industrial perspective, the recommendations of this study emphasize the need to increase the capacity and understanding of HVAC practitioners towards natural refrigerant technology. The study's conclusions suggest that doubts over the technical and economic feasibility of natural refrigerants remain the main obstacles to implementation. Therefore, further research can be focused on case studies of the application of natural refrigerant-based HVAC systems in the field to provide concrete evidence regarding the performance, reliability, and environmental benefits of the system.

Fifth, based on the policy implications implied in the research conclusions, it is recommended that follow-up research examine the role of regulations and technical standards in encouraging the adoption of environmentally friendly refrigeration technology. This study shows that natural refrigerant-based HVAC system design has great potential in supporting carbon emission reduction, so harmonized policy support is needed. This policy study can be a bridge between the results of academic research and the implementation of technology at the national and international levels.

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