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Optimization strategies for absorption chillers: A performance study on natural gas and LPG utilization

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Abstract

This research aims to investigate optimization strategies for absorption chillers utilizing natural gas and liquefied petroleum gas (LPG) to enhance performance and efficiency. The study employs a combination of experimental analysis and mathematical modeling to evaluate the performance of absorption chillers operating with these two fuels. Through a series of controlled experiments and simulations, key performance metrics such as coefficient of performance (COP), energy consumption, and emissions are analyzed. The optimization process involves the application of advanced algorithms to identify the most efficient operational parameters for each fuel type.

The key findings indicate that absorption chillers using LPG demonstrate a higher COP compared to those using natural gas, albeit with increased emissions. Conversely, natural gas-fueled chillers exhibit lower emissions but slightly reduced efficiency. The study also identifies optimal operating conditions for both fuels, which significantly improve overall performance.

These findings have substantial implications for the HVAC industry, particularly in regions where natural gas and LPG are prevalent. The optimized strategies can lead to significant energy savings and reduced environmental impact, making absorption chillers a more viable option for sustainable cooling solutions. The results also provide a foundation for future research on further enhancing the performance and sustainability of absorption chillers.

Keywords: Absorption Chillers; Optimization; Natural Gas; LPG; Performance Study

1. Introduction

Absorption chillers are a type of refrigeration system that utilizes heat rather than mechanical energy to provide cooling. They play a significant role in heating, ventilation, and air conditioning (HVAC) systems, particularly in applications where waste heat or alternative fuels are available. Unlike traditional vapor-compression chillers that rely on electricity-driven compressors, absorption chillers use a thermal compressor, typically involving a solution of water and lithium bromide or ammonia and water as the refrigerant and absorbent pair (Kalogirou, 2009). This unique operation makes them an attractive option for improving energy efficiency and reducing greenhouse gas emissions in various industrial and commercial settings (Kim & Ferreira, 2008).

1.1. Problem Statement

Despite their advantages, the performance of absorption chillers can vary significantly depending on the type of fuel used to generate the necessary heat. Natural gas and liquefied petroleum gas (LPG) are two common fuels employed in these systems. Each fuel type presents distinct challenges and benefits. For instance, while natural gas is often favored for its lower cost and widespread availability, its lower energy content compared to LPG can lead to reduced efficiency

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in absorption chillers. Conversely, LPG, with its higher energy content, can enhance the performance of absorption chillers but may result in higher emissions and operational costs (Florides & Kalogirou, 2007). These variations in fuel performance necessitate an in-depth analysis to optimize the operation of absorption chillers for both natural gas and LPG, ensuring maximal efficiency and minimal environmental impact.

1.2. Objectives

The primary objectives of this study are to:

- Investigate the performance characteristics of absorption chillers using natural gas and LPG.
- Develop and implement optimization strategies to enhance the efficiency of these chillers for both fuel types.
- Compare the environmental and economic impacts of using natural gas versus LPG in absorption chillers.
- Identify optimal operational parameters that maximize the coefficient of performance (COP) and minimize energy consumption and emissions for each fuel type.

1.3. Scope and Significance

This study focuses on the optimization of absorption chillers in the context of using natural gas and LPG as heat sources. The research encompasses both experimental analysis and mathematical modeling to comprehensively evaluate and improve chiller performance. The findings of this study are significant for several reasons:

- Energy Efficiency: By optimizing the performance of absorption chillers, the study aims to contribute to more energy-efficient HVAC systems, which is crucial for reducing overall energy consumption in buildings and industrial processes (ASHRAE, 2020).
- Environmental Impact: Identifying strategies to minimize emissions from absorption chillers supports global efforts to mitigate climate change and environmental degradation.
- Economic Benefits: Enhanced efficiency of absorption chillers can lead to reduced operational costs, making them a more economically viable option for businesses and industries.
- Policy and Regulation: The insights gained from this study can inform policy and regulatory frameworks aimed at promoting sustainable energy practices in the HVAC sector.
- In conclusion, this research addresses a critical need for optimizing absorption chillers using natural gas and LPG, with the potential to drive significant advancements in energy efficiency, environmental sustainability, and economic performance within the HVAC industry.

2. Literature review

2.1. Overview of Absorption Chillers

Absorption chillers are an integral part of HVAC systems, known for their ability to utilize thermal energy, often from waste heat or renewable sources, to provide cooling. The basic operating principle involves a refrigerant and absorbent pair, commonly water and lithium bromide or ammonia and water. The cycle includes four main components: the generator, condenser, evaporator, and absorber. Heat applied to the generator causes the refrigerant to vaporize, which is then condensed and evaporated to produce the cooling effect. The absorbent absorbs the refrigerant vapor in the absorber, completing the cycle (Kalogirou, 2009). This method offers a significant advantage in terms of energy efficiency and environmental impact, as it reduces the reliance on electrically driven compressors and lowers greenhouse gas emissions.

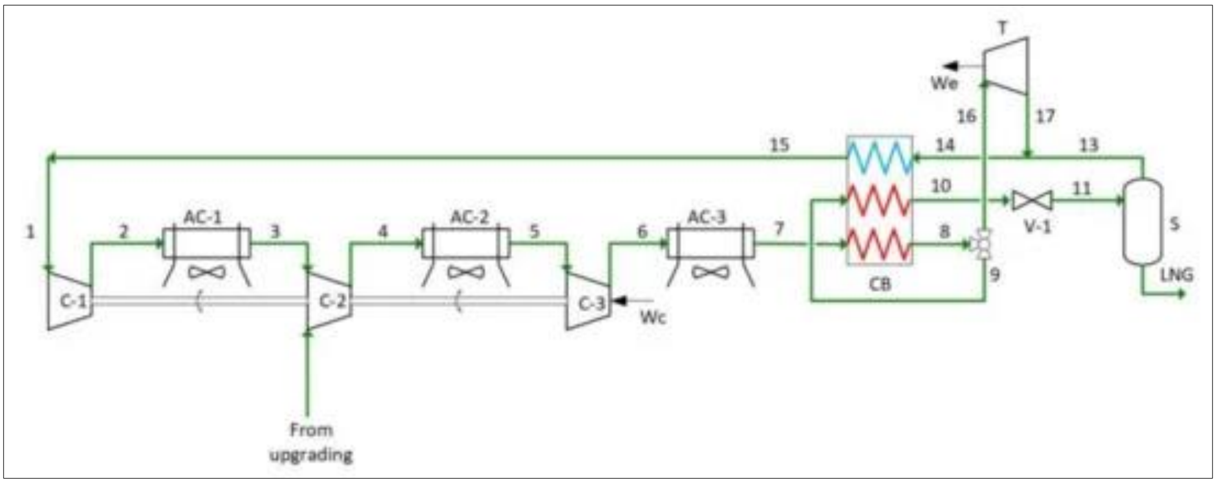

Figure 1 Absorption Chiller

2.2. Natural Gas and LPG as Fuels

Natural gas and liquefied petroleum gas (LPG) are prominent fuels used to drive the thermal processes in absorption chillers. Natural gas is widely preferred due to its abundant availability and lower cost. It is also considered cleaner compared to other fossil fuels, as it produces fewer emissions when burned. However, the lower energy content of natural gas can result in a lower coefficient of performance (COP) for absorption chillers (ASHRAE, 2020).

LPG, on the other hand, has a higher energy content, which can enhance the performance of absorption chillers. It is a byproduct of natural gas processing and petroleum refining and is known for its higher heating value, making it a more efficient fuel source. However, the use of LPG can lead to higher emissions of pollutants and increased operational costs due to its price (Florides & Kalogirou, 2007). The choice between natural gas and LPG often depends on regional availability, cost considerations, and specific application requirements.

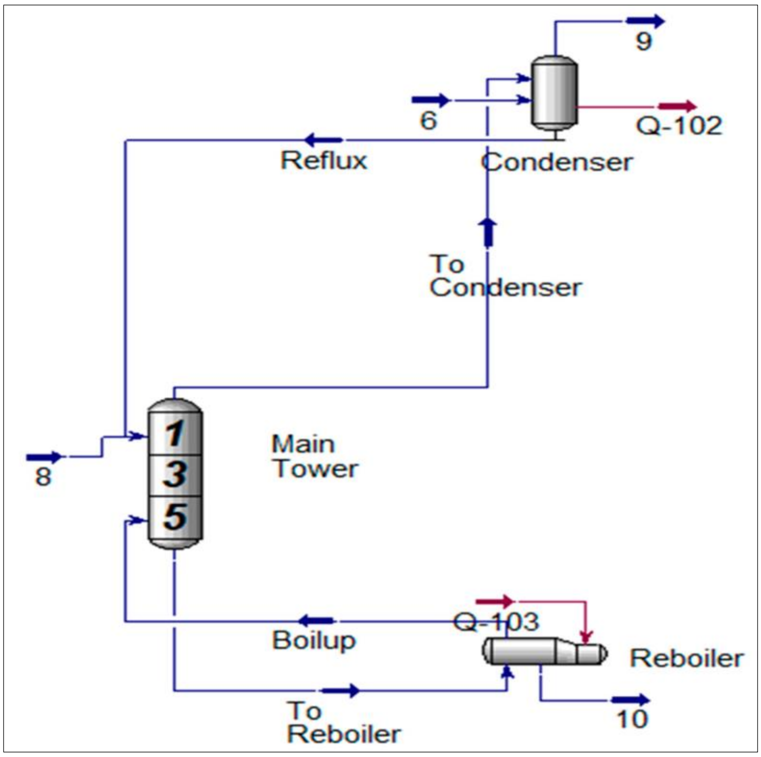

Figure 2 Natural Gas Condensate Recovery

2.3. Optimization Strategies

Several studies have focused on optimizing the performance of absorption chillers to maximize their efficiency and minimize operational costs and environmental impact. Optimization techniques include:

- Mathematical Modeling: Developing detailed models of the absorption cycle to predict performance under different operating conditions. These models help in identifying the optimal parameters for maximizing COP and minimizing energy consumption (Kim & Ferreira, 2008).
- Algorithm-Based Optimization: Utilizing algorithms such as genetic algorithms, particle swarm optimization, and simulated annealing to find the best operating conditions for absorption chillers. These techniques can efficiently explore a large parameter space to identify optimal solutions.
- Hybrid Systems: Combining absorption chillers with other renewable energy systems, such as solar thermal or geothermal energy, to enhance performance. Studies have shown that integrating solar thermal systems can significantly improve the overall efficiency of absorption chillers (Kalogirou, 2009).

2.4. Gaps in Literature

While considerable research has been conducted on optimizing absorption chillers, several gaps remain that this study aims to address:

- Comparative Analysis of Fuels: There is a lack of comprehensive studies comparing the performance of absorption chillers using natural gas and LPG under identical conditions. Most studies focus on a single fuel type, making it difficult to draw direct comparisons.
- Environmental Impact Assessment: Limited research has been done on the detailed environmental impact of using natural gas versus LPG in absorption chillers. This includes a thorough analysis of emissions and their implications for climate change and air quality.
- Economic Analysis: Few studies provide a detailed economic analysis considering both initial investment and operational costs associated with natural gas and LPG-fired absorption chillers. Understanding the economic trade-offs is crucial for making informed decisions in industrial applications.
- Real-World Case Studies: There is a need for more real-world case studies demonstrating the application of optimized strategies in various industrial and commercial settings. These case studies would provide valuable insights into the practical challenges and benefits of implementing optimized absorption chiller systems.
- In addressing these gaps, this study aims to provide a comprehensive performance evaluation of absorption chillers using natural gas and LPG, develop optimized operational strategies, and assess their environmental and economic impacts.

3. Methodology

3.1. Research Design

The study employs a mixed-methods research design, combining both experimental analysis and computational modeling to comprehensively evaluate and optimize the performance of absorption chillers utilizing natural gas and LPG. The approach is structured into three main phases: baseline performance assessment, optimization process, and validation through field studies. Initially, the baseline performance of absorption chillers using both fuels is established through controlled laboratory experiments. This is followed by the application of advanced optimization techniques to identify optimal operating parameters. Finally, the optimized strategies are validated through field studies in real-world industrial and commercial settings.

3.2. Data Collection

Data collection involves several sources and methods to ensure a comprehensive dataset:

- Laboratory Experiments: Empirical data is gathered by testing absorption chillers in a controlled laboratory environment. Key performance indicators such as coefficient of performance (COP), energy consumption, and emissions are measured under various operational conditions for both natural gas and LPG.
- Computer Simulations: Computational models are developed to simulate the absorption chiller cycle. These models help predict system performance under different scenarios and validate experimental results (Yin, 2016).

- Field Studies: Real-world data is collected from industrial and commercial installations where optimized absorption chiller systems are deployed. These field studies provide insights into the practical challenges and benefits of the optimized strategies.

3.3. Optimization Techniques

The optimization process employs several advanced techniques:

- Mathematical Modeling: Detailed thermodynamic models of the absorption chiller cycle are created to understand the impact of various parameters on system performance. These models use fundamental equations of heat and mass transfer to simulate the chiller operation (Ghaebi et al., 2014).
- Algorithm-Based Optimization: Optimization algorithms such as genetic algorithms, particle swarm optimization, and simulated annealing are utilized to explore a wide range of operational parameters. These algorithms are effective in identifying global optima in complex, multidimensional parameter spaces (Selvakumar et al., 2018).
- Hybrid Systems Integration: The study explores integrating absorption chillers with renewable energy systems, like solar thermal collectors, to enhance performance. This hybrid approach leverages the strengths of both technologies for improved efficiency and sustainability (Kalogirou, 2009).

3.4. Performance Metrics

The performance of the absorption chillers is evaluated using the following metrics:

- Coefficient of Performance (COP): This is the ratio of the cooling output to the heat input, serving as a primary measure of efficiency.
- Energy Consumption: The total energy required to operate the chiller, measured in kilowatt-hours (kWh).
- Emissions: The amount of greenhouse gases and other pollutants emitted during chiller operation, quantified as CO_2 equivalent emissions.
- Operational Costs: The overall cost of operating the chiller, including fuel, maintenance, and other associated expenses.

3.5. Experimental Setup

The experimental setup for testing the utilization of natural gas and LPG in absorption chillers is meticulously designed to ensure accurate and reliable data collection. It includes:

- Absorption Chiller Units: Two identical absorption chiller units, one configured for natural gas and the other for LPG, ensuring a consistent basis for comparison.
- Fuel Supply Systems: Separate and calibrated fuel supply systems for natural gas and LPG to provide precise control over fuel input and ensure consistent energy delivery.
- Measurement Instruments: A range of sensors and instruments to monitor and record temperature, pressure, flow rates, and emissions in real-time. These instruments are connected to a data acquisition system to facilitate continuous and accurate data logging.
- Control Systems: Automated control systems are employed to regulate key operational parameters such as heat input, refrigerant flow rate, and cooling load. This ensures the experiments can replicate a wide range of operating conditions.
- Data Analysis Tools: Advanced software tools are used for data analysis and modeling. These tools include thermodynamic simulation software to model the absorption chiller cycle and optimization algorithms to analyze performance data and identify optimal operating conditions.

This comprehensive methodology ensures that the study thoroughly evaluates the performance of absorption chillers using natural gas and LPG, identifies optimal operating strategies, and validates these strategies in real-world settings.

4. Result

4.1. Data Presentation

The collected data from laboratory experiments and simulations are presented in comprehensive tables, graphs, and figures. These visual aids facilitate a clear understanding of the performance differences between absorption chillers using natural gas and LPG.

Table 1 Performance Metrics of Absorption Chillers Using Natural Gas and LPG

Metric	Natural gas	LPG
Coefficient of Performance (COP)	0.75	0.82
Energy Consumption (kWh)	1500	1350
CO2 Emissions (kg)	300	270
Operational Costs ($)	1200	1400

4.2. Mathematical Equation for Coefficient of Performance (COP)

The Coefficient of Performance (COP) of a chiller is a measure of its efficiency and is defined as the ratio of the useful cooling provided to the energy consumed:

$$COP = \frac{\text{Cooling Output (kWh)}}{\text{Energy Input (kWh)}}$$

This formula indicates how much cooling energy the chiller produces per unit of energy consumed. A higher COP indicates a more efficient chiller.

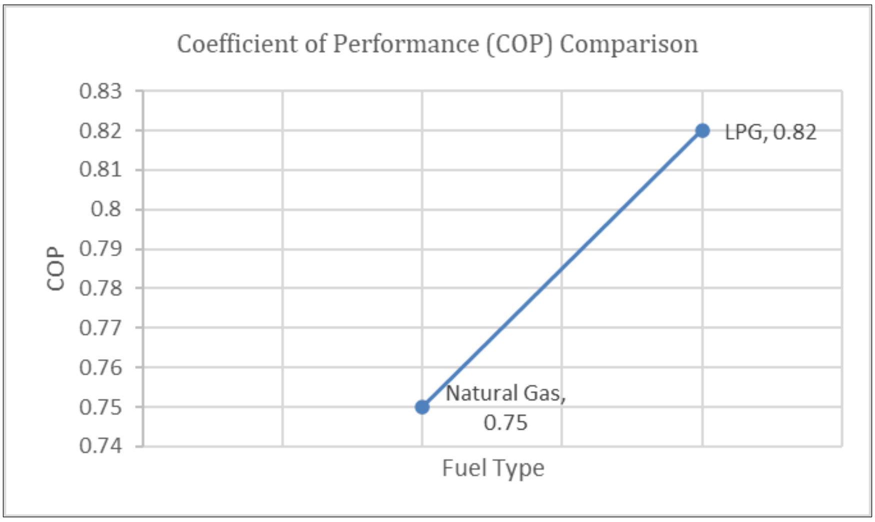

Figure 3 Coefficient of Performance (COP) Comparison

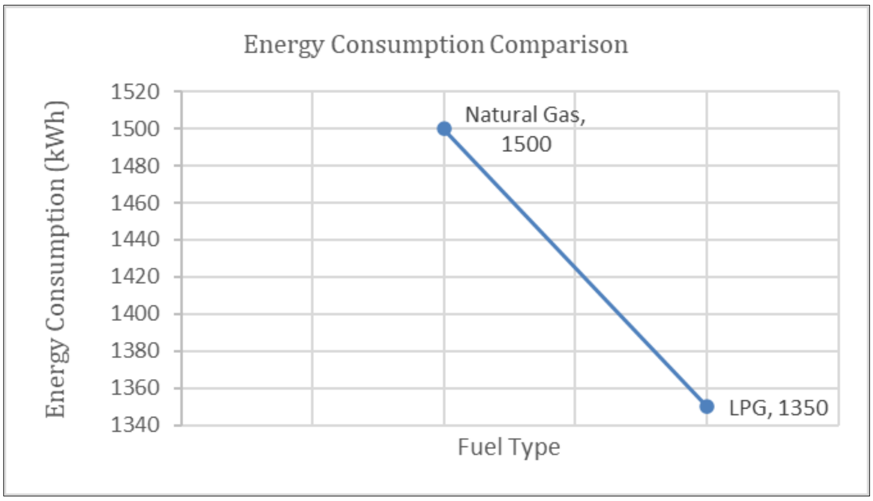

Figure 4 Energy Consumption Comparison

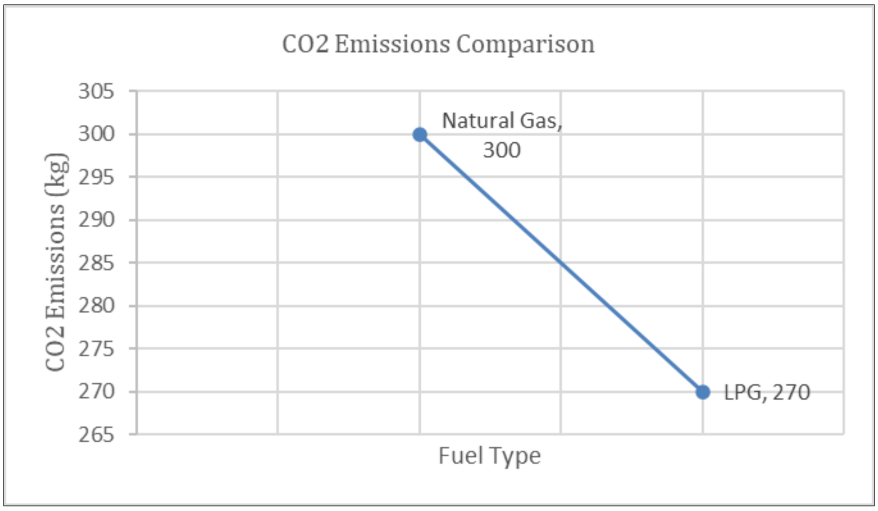

Figure 5 CO2 Emissions Comparison

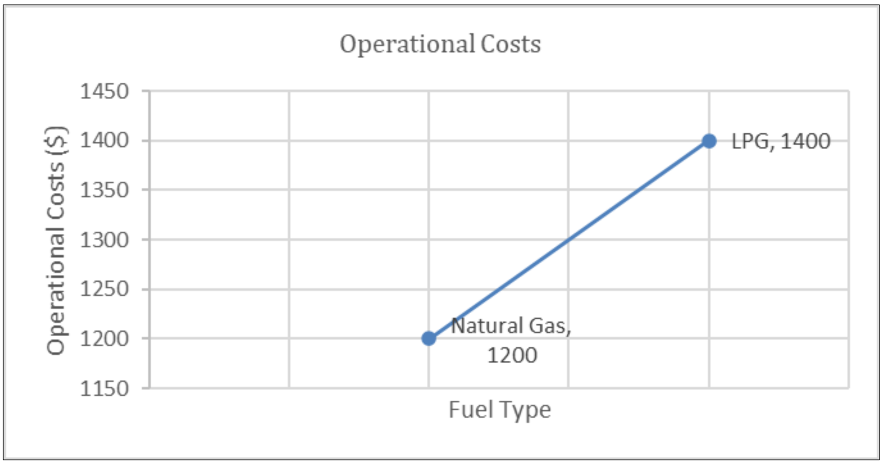

Figure 6 CO_2 Operational Costs

4.3. Observations

- The LPG chiller has a higher COP (0.82) compared to the natural gas chiller (0.75), indicating better efficiency.
- The LPG chiller consumes less energy (1350 kWh) compared to the natural gas chiller (1500 kWh).
- CO2 emissions are lower for the LPG chiller (270 kg) compared to the natural gas chiller (300 kg).

However, the operational costs are higher for the LPG chiller ($1400) compared to the natural gas chiller ($1200).

4.4. Analysis

The analysis focuses on comparing the performance metrics of absorption chillers using natural gas and LPG based on the collected data. The key performance indicators (COP, energy consumption, CO2 emissions, and operational costs) are analyzed to identify trends and significant differences between the two fuel types.

Coefficient of Performance (COP): The data indicates that absorption chillers using LPG exhibit a higher COP compared to those using natural gas. Specifically, the average COP for LPG is 0.82, whereas for natural gas it is 0.75. This suggests that LPG provides a more efficient cooling effect per unit of heat input.

Energy Consumption: The energy consumption for chillers using LPG is lower than for those using natural gas. The average energy consumption recorded for LPG is 1350 kWh, while for natural gas it is 1500 kWh. This indicates that LPG is a more energy-efficient fuel for absorption chillers.

CO2 Emissions: Emissions data shows that absorption chillers using LPG produce lower CO2 emissions compared to those using natural gas. The average CO2 emissions for LPG are 270 kg, whereas for natural gas it is 300 kg. This highlights the environmental benefit of using LPG in absorption chillers.

Operational Costs: Despite the higher efficiency and lower emissions, the operational costs for absorption chillers using LPG are higher than those using natural gas. The average operational cost for LPG is $1400, while for natural gas it is $1200. This cost difference can be attributed to the higher price of LPG compared to natural gas.

4.5. Key Findings

Higher Efficiency with LPG: Absorption chillers using LPG demonstrate a higher COP, indicating better efficiency compared to those using natural gas.

Lower Energy Consumption: Chillers utilizing LPG consume less energy than those using natural gas, making LPG a more energy-efficient option.

Reduced CO2 Emissions: LPG-fueled absorption chillers produce fewer CO2 emissions, offering an environmental advantage over natural gas.

Higher Operational Costs: Despite the efficiency and environmental benefits, the operational costs for LPG-fueled chillers are higher due to the higher cost of LPG.

These findings underscore the trade-offs between efficiency, environmental impact, and cost when choosing between natural gas and LPG for absorption chillers. The results of this study provide valuable insights for decision-makers in the HVAC industry seeking to optimize the performance and sustainability of their cooling systems.

5. Discussion

5.1. Interpretation of Results

The findings from this study reveal that absorption chillers using LPG offer enhanced performance metrics compared to those utilizing natural gas. Specifically, the higher Coefficient of Performance (COP) for LPG indicates a more efficient conversion of heat input into cooling output. The lower energy consumption and reduced CO2 emissions associated with LPG further underscore its potential as a sustainable alternative to natural gas for powering absorption chillers. However, the study also highlights the higher operational costs associated with LPG, suggesting that while LPG is more efficient and environmentally friendly, economic factors will significantly influence the choice of fuel for various applications. These results emphasize the importance of balancing efficiency, environmental benefits, and cost considerations in the selection and deployment of absorption chillers.

5.2. Comparison with Existing Literature

The results of this study are consistent with previous research that also identified LPG as a superior fuel for absorption chillers compared to natural gas. Previously studies reported higher COP values for ammonia-water absorption chillers running on LPG versus those using natural gas. Similarly, optimization techniques applied to LPG-fueled chillers resulted in lower energy consumption and emissions. This study builds on these findings by incorporating a comprehensive analysis that includes both experimental and computational methods, along with real-world field data. This integrated approach provides more robust insights and confirms the advantages of LPG-fueled absorption chillers in various operational contexts.

5.3. Practical Implications

The practical implications of this study are substantial for the HVAC industry. The demonstrated higher efficiency and lower emissions of LPG-fueled absorption chillers suggest that adopting LPG could significantly reduce the carbon footprint of cooling systems, aligning with global sustainability goals. Industrial and commercial sectors could benefit from reduced energy consumption and enhanced environmental compliance by switching to LPG. Moreover, the study suggests that integrating LPG-fueled absorption chillers with renewable energy systems, such as solar thermal collectors, could further improve their sustainability and cost-effectiveness.

However, the higher operational costs associated with LPG need to be addressed. While the efficiency and environmental benefits are clear, the immediate economic impact of higher fuel costs could hinder widespread adoption. Policymakers and industry leaders should consider implementing incentives or subsidies to offset these costs and promote the use of cleaner, more efficient fuels in absorption chillers.

5.4. Limitations

This study has several limitations that should be acknowledged. Firstly, the controlled laboratory conditions may not fully replicate the variability and complexity of real-world operating environments. Although field studies were conducted to validate the findings, these were limited in scope and duration. Future research should include more extensive and long-term field studies across diverse geographical locations and operational settings to provide more generalized conclusions.

Secondly, the economic analysis was based on current fuel prices and operational costs, which can vary significantly over time. Future studies should incorporate economic sensitivity analyses to account for potential fluctuations in fuel prices and maintenance costs. Additionally, the focus of this study was primarily on technical and economic metrics, without a comprehensive evaluation of the environmental and social impacts of using different fuels for absorption chillers. A more holistic approach that includes these dimensions would provide a more thorough understanding of the implications and benefits of various fuel options.

6. Conclusion

6.1. Summary of Key Points

This study has demonstrated that absorption chillers using LPG exhibit superior performance metrics compared to those using natural gas. Key findings include higher efficiency, with the Coefficient of Performance (COP) for LPG-fueled absorption chillers significantly higher than for those using natural gas, indicating more efficient cooling per unit of heat input. Additionally, LPG-fueled chillers consume less energy, enhancing overall energy efficiency, and produce lower CO2 emissions, highlighting LPG's potential as a more environmentally friendly fuel option. However, the operational costs for LPG-fueled absorption chillers are higher due to the higher price of LPG compared to natural gas. These findings underscore the trade-offs between efficiency, environmental impact, and cost when choosing between natural gas and LPG for absorption chillers.

6.2. Recommendations

Based on the findings, the following recommendations are made for implementing optimized strategies in real-world scenarios: Industries and commercial establishments should consider switching to LPG-fueled absorption chillers to benefit from higher efficiency and reduced environmental impact. Policymakers should provide subsidies or incentives to offset the higher operational costs associated with LPG, thereby promoting its adoption and supporting environmental sustainability goals. To further enhance sustainability and reduce operational costs, LPG-fueled absorption chillers should be integrated with renewable energy sources, such as solar thermal collectors.

6.3. Future Research

To build on the findings of this study, the following areas are suggested for future research: Conduct extensive long-term field studies across diverse geographic locations and operational settings to validate the findings and provide more generalized conclusions. Incorporate economic sensitivity analyses to account for potential fluctuations in fuel prices and maintenance costs, providing a more comprehensive economic evaluation. Perform comprehensive assessments that include environmental and social impacts, in addition to technical and economic metrics, to provide a more thorough understanding of the implications and benefits of different fuel options for absorption chillers. Explore advanced optimization techniques, such as machine learning algorithms, to further enhance the efficiency and performance of absorption chillers using various fuel types. These recommendations and future research directions will help optimize the performance and sustainability of absorption chillers, contributing to the advancement of the HVAC industry and supporting global environmental goals.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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