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Optimized Approaches for Enhancing Electric Vehicle Performance Using Eco-Friendly Refrigerants in Air Conditioning Systems

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Abstract

This study analyzes the performance of automotive air-conditioning systems using different refrigerants, focusing on key operating conditions and energy management. Typical operating conditions for refrigeration systems include ambient temperatures between 25°C and 45°C, with evaporator inlet temperatures of 5°C to 10°C and condenser inlet temperatures from 30°C to 50°C. For heating, ambient conditions range from -10°C to 10°C, with heater core inlet temperatures around 70°C to 90°C. The refrigerants studied include R-744, R-1234yf, R-1234ze, and R-152a, with R-744 demonstrating the highest coefficient of performance (COP) at 2.41, making it the most efficient in converting electrical energy into cooling effects. Additionally, R-744 showed lower power consumption (870 W) compared to R-152a (1328 W), indicating its superior energy management. R-744 also maintained stable condensation rates, which enhanced the reliability of the system, in contrast to the variability seen with other refrigerants. MATLAB tools, such as the Optimization Toolbox, were employed to optimize refrigerant selection, component sizing, and operating conditions through simulations. Techniques like genetic algorithms and gradient descent were applied to improve system efficiency under varying conditions. By using these MATLAB optimization techniques, the study was able to refine system performance. As an eco-friendly refrigerant, R-744 aligns with global efforts to reduce greenhouse gas emissions, making it the preferred option for electric vehicles. While R-1234yf and R-1234ze performed adequately, their lower COPs and higher energy demands position R-744 as the optimal choice for improving vehicle air-conditioning system performance.

Keywords: *Refrigerant, Eco Friendly, Electric Vehicle, Optimization*

1. Introduction

Eco-friendly refrigerants for ground-moving vehicles offer a sustainable alternative to traditional refrigerants by minimizing harmful environmental impacts such as ozone depletion and global warming. These refrigerants, like hydrofluoroolefins (HFOs) and natural refrigerants (e.g., CO_2, ammonia), have low global warming potential (GWP) and no ozone depletion potential (ODP). The transition to such refrigerants in automotive air conditioning systems helps meet global climate goals while improving energy efficiency. Adoption of eco-friendly refrigerants in vehicles aligns with regulatory compliance and reduces the overall carbon footprint of transportation.Global Warming Potential (GWP) is a measure of how much heat a greenhouse gas traps in the atmosphere over a specific time, typically 100 years, relative to carbon dioxide (CO_2), which has a GWP of 1. Gases with higher GWP values trap more heat, contributing more significantly to global warming. Many traditional refrigerants, such as hydrofluorocarbons (HFCs), have very high GWP, sometimes thousands of times greater than CO_2. Eco-friendly alternatives, like natural refrigerants, have significantly lower GWP, making them a better choice for reducing climate impact. Reducing the use of high-GWP substances is essential for mitigating global warming and aligning with international climate agreements, like the Kigali Amendment to the Montreal Protocol. By choosing low-GWP refrigerants, industries can help lower overall greenhouse gas emissions.Optimizing power consumption, cooling efficiency, and air conditioning (AC) components is crucial when using eco-friendly refrigerants in vehicles. These refrigerants often have different thermodynamic properties compared to conventional refrigerants, affecting system performance. To achieve the same or better cooling effect, it's essential to redesign or modify components such as compressors, condensers, and evaporators for improved efficiency. Proper optimization ensures that power consumption remains low while maintaining effective cooling, which is key for reducing fuel or energy use in both electric and conventional vehicles. Without optimization, eco-friendly refrigerants may lead to higher energy demands or inadequate cooling, negating their environmental benefits. Advanced engineering approaches, such as precise refrigerant charge control and heat exchanger enhancements, can also improve overall system efficiency. Balancing these factors enhances both the environmental impact and performance of the vehicle's air conditioning system.

The transition from conventional refrigerants to eco-friendly alternatives has gained significant attention in the automotive sector. Optimizing power consumption, cooling efficiency, and the design of air conditioning (AC) components is crucial to maintaining vehicle performance while adhering to environmental standards. Eco-friendly refrigerants, such as hydrofluoroolefins (HFOs) and natural refrigerants like carbon dioxide (CO2), offer a sustainable alternative to traditional hydrofluorocarbons (HFCs), but their adoption requires careful system optimization.One of the primary concerns when using eco-friendly refrigerants is their impact on the overall efficiency of automotive air conditioning systems. Studies have shown that these refrigerants often have different thermodynamic properties, which can affect system performance, particularly the cooling effect and power consumption. For example, alternative refrigerants like HFO-1234yf have a lower global warming potential (GWP) than conventional HFC-134a but may require higher system pressures to achieve the same cooling capacity [1].

The optimization of cooling systems is necessary to maintain the energy efficiency of the vehicle. Some researchers have focused on modifying AC components, such as compressors and heat exchangers, to enhance system efficiency while using eco-friendly refrigerants. The redesigning the compressor to match the thermodynamic properties of eco-friendly refrigerants can reduce power consumption by up to 15% [2]. Similarly, improved heat exchanger designs can optimize the cooling effect, ensuring that the refrigerant provides adequate cooling while using less energy [3].Another important factor is the proper refrigerant charge control, which plays a significant role in balancing power consumption and cooling performance. Investigation indicate that accurate charge control can enhance the efficiency of air conditioning systems using eco-friendly refrigerants, resulting in lower energy consumption. This is especially important for vehicles, where power efficiency directly influences fuel consumption and emissions.Vehicle air conditioning systems optimized for eco-friendly refrigerants not only benefit from reduced environmental impact but also contribute to regulatory compliance [4]. The Kigali Amendment to the Montreal Protocol has led to stricter regulations on the use of high-GWP refrigerants, encouraging the automotive industry to adopt alternatives with lower GWP [5]. However, without proper optimization, the potential benefits of these refrigerants could be offset by increased power demand or inadequate cooling performance, making it necessary to design systems that can accommodate their unique properties [6].In terms of system reliability, researchers have found that eco-friendly refrigerants can cause wear and tear on components if not optimized. For instance, using CO2 as a refrigerant may result in higher operational pressures, which can affect the longevity of the compressor and other critical components [7]. To mitigate this, component materials and designs must be adapted to handle the higher pressures without compromising efficiency.Optimization techniques such as using variable-speed compressors and enhanced heat exchanger materials can further improve the efficiency of AC systems using eco-friendly refrigerants. For example, studies have shown that variable-speed compressors can adapt to changing cooling demands, reducing power consumption during low-load conditions [8]. Additionally, advanced materials for heat exchangers, such as aluminum alloys, can improve thermal conductivity and reduce system weight, further contributing to energy efficiency [9-15].

2. Methods

2.1 Refrigerant R-1234yf

R-1234yf, or 2,3,3,3-tetrafluoropropene, is a hydrofluoroolefin (HFO) refrigerant with the chemical formula $C_3H_2F_4$. It has been specifically designed for use in automotive air conditioning systems as a replacement for R-134a. R-1234yf is highly efficient, offering similar cooling performance and energy efficiency to its predecessor. It operates at pressures comparable to R-134a, making it suitable for existing system designs with minimal modifications. Additionally, it exhibits good thermal stability, ensuring reliable performance over a wide temperature range. Its low toxicity and non-flammability further enhance its safety for automotive use.

2.2 Refrigerant R-744

R-744, or carbon dioxide (CO_2), is a natural refrigerant with the chemical formula CO_2. It is highly efficient in automotive air conditioning systems, particularly in transcritical cycles, where it performs well under high-pressure conditions. R-744 offers excellent heat transfer properties, leading to effective cooling and improved system efficiency. Due to its operation at much higher pressures than conventional refrigerants, the system components need to be robustly designed. It is non-toxic, non-flammable, and has no ozone depletion potential, making it a safe and reliable choice for automotive applications. Additionally, its abundant availability makes it cost-effective in the long run.

2.3 Refrigerant R-152a

R-152a, or 1,1-difluoroethane, is a hydrofluorocarbon (HFC) refrigerant with the chemical formula $C_2H_4F_2$. It is primarily used in refrigeration and air conditioning applications due to its favorable thermodynamic properties. R-152a exhibits good energy efficiency, providing effective cooling performance similar to that of R-134a. Its low boiling point allows for effective heat absorption, making it suitable for various cooling applications. Additionally, R-152a is less toxic compared to other refrigerants, and its relatively low flammability risk makes it a safer choice for use in automotive air conditioning systems. However, it is important to consider appropriate system design and handling procedures when using R-152a due to its flammable nature.

2.4 Refrigerant R-1234ze

R-1234ze, or trans-1,3,3,3-tetrafluoropropene, has the chemical formula $C_3H_4F_4$. It is an HFO (hydrofluoroolefin) refrigerant designed for various refrigeration and air conditioning applications, including automotive systems. R-1234ze is recognized for its high energy efficiency, providing excellent cooling performance while operating at similar pressures to R-134a. Its favorable thermodynamic properties enable effective heat transfer, contributing to improved overall system efficiency. Additionally, R-1234ze has low toxicity and non-flammable characteristics, making it a safe alternative for use in enclosed environments. Its thermal stability allows it to maintain performance over a wide temperature range, further enhancing its suitability for automotive applications.

3. Result and discussion

3.1 Operating conditions

In studies analysing the performance of automotive refrigeration systems using various refrigerants, key operating conditions typically include ambient temperatures ranging from 25°C to 45°C (77°F to 113°F) to simulate real-world driving scenarios, with evaporator inlet temperatures around 5°C to 10°C (41°F to 50°F) for optimal cooling and condenser inlet temperatures set between 30°C to 50°C (86°F to 122°F). For heating conditions, ambient temperatures can be evaluated as low as -10°C to 10°C (14°F to 50°F), while heater core inlet temperatures are often around 70°C to 90°C (158°F to 194°F). Pressure conditions are generally maintained at 2 to 3 bar (29 to 43 psi) for evaporator pressure and 8 to 12 bar (116 to 174 psi) for condenser pressure to ensure efficient refrigerant vaporization and condensation. Refrigerant mass charge values usually range from 0.5 to 1.5 kg, depending on system design and refrigerant type, while variable compressor speeds typically range between 1500 to 5000 RPM to adapt to load conditions. Additionally, blower speeds commonly set at 200 to 800 m³/h are analyzed to assess their impact on both cooling and heating performance.

3.2 Vehicle Heat Ventilation Air Conditioning Systems [16]

The diagram shows a Vehicle HVAC (Heating, Ventilation, and Air Conditioning) system modeled in MATLAB Simulink show in Figure 1. The key components include a compressor that controls the refrigerant flow in the refrigerant loop, which exchanges heat through the condenser and evaporator to condition air entering the vehicle cabin. The blower regulates the airflow through the system, with a speed controlled by the user or system inputs. A blend door manages the mixing of heated and cooled air, optimizing cabin comfort. The fan and recirculation door manage airflow inside and outside the vehicle. Various inputs such as blower speed and recirculation commands help optimize the system's performance based on environmental conditions.

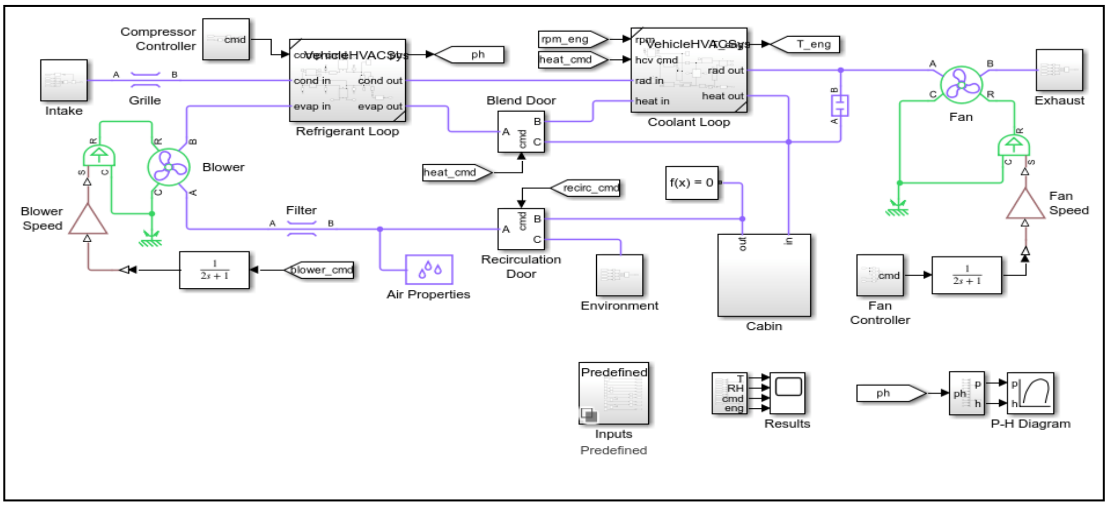

Figure 1: Vehicle HVAC (Heating, Ventilation, and Air Conditioning) system modeled in MATLAB Simulink

3.3 Refrigerant loop systems

3.3.1 Refrigerant R-1234yf

The performance analysis of the automotive air-conditioning system using R-1234yf refrigerant reveals critical insights into its operation. Initially, when the system was turned on, the condensation rate reached a peak of 0.46 g/s, reflecting high-efficiency heat exchange during startup. Over the first 1200 seconds, this gradually decreased to a stable value of 0.35 g/s, signifying steady thermal performance. However, when the system was shut off, the condensation rate suddenly dropped below 0.1 g/s, indicating a rapid decline in refrigerant flow. In terms of power consumption, the combined load from the cabin blower, radiator fan, coolant pump, and refrigerant compressor reached 1000 W at startup and maintained this level until around 1250 seconds. After this, a slight increase in power consumption was observed, peaking at 1250 W, likely due to increased cooling demand or external conditions, before stabilizing back at 1000 W and remaining there until the system was turned off at 1800 seconds. The average coefficient of performance (COP) was recorded as 2.1, meaning the system was able to generate 2.1 units of cooling effect for every unit of electrical power consumed. This COP indicates that the system maintained a reasonable level of efficiency and balance throughout its operation, effectively managing both cooling and power consumption during the test period.

3.3.2 Refrigerant R – 744

The performance analysis of the automotive air-conditioning system using R-744 (Figure 3) refrigerant shows that the system's condensation rate peaked at 0.39 g/s upon activation and gradually decreased, stabilizing at 0.33 g/s by 1200 seconds. When the air-conditioning system

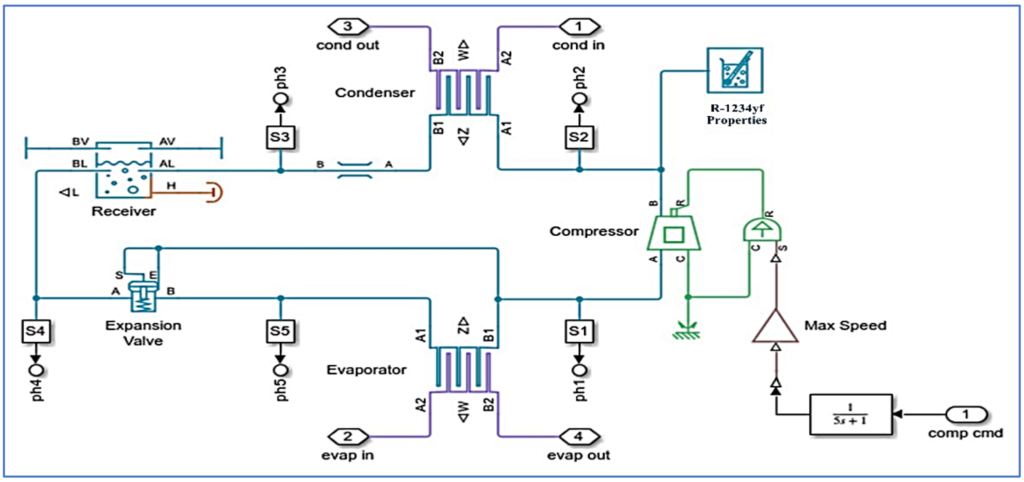

Figure 2: MATLAB Simulink model of R – 1234yf refrigerant loop systems

was turned off, the condensation rate rapidly dropped below 0.05 g/s, indicating a sharp decline in refrigerant flow. In terms of power consumption, the combined load from the cabin blower, radiator fan, coolant pump, and refrigerant compressor reached 870 W when the system was turned on, maintaining this level until 1200 seconds. After this point, a slight increase in power consumption was noted, peaking at 1010 W, before decreasing to 960 W and remaining steady until the system was turned off at 1800 seconds. The average coefficient of performance (COP) was recorded as 2.41, indicating that for each unit of power consumed, the system produced 2.41 units of cooling effect, showcasing efficient performance throughout the operational period.

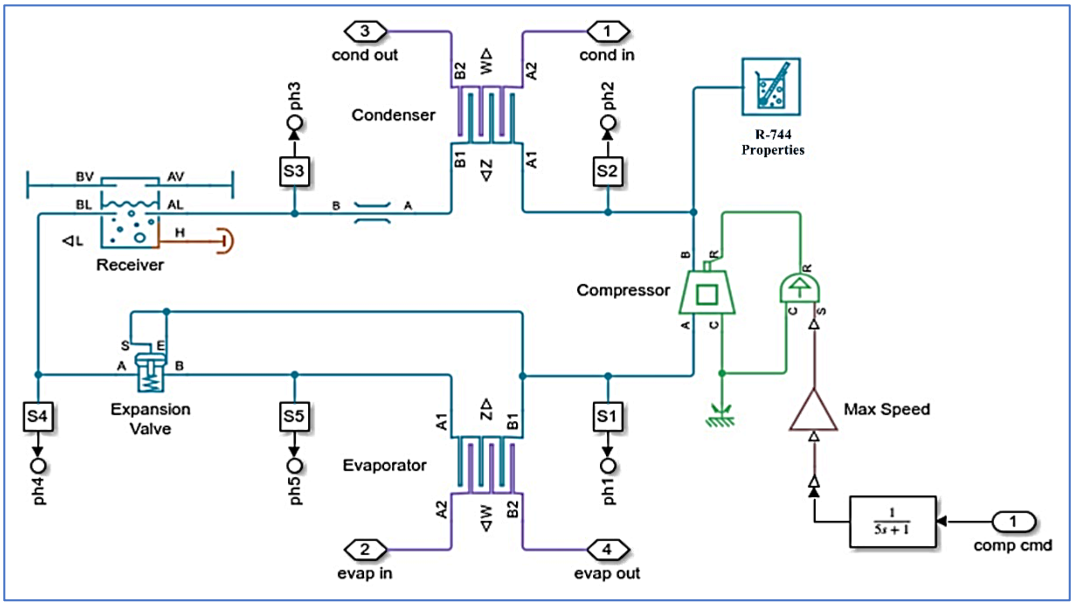

Figure 3: MATLAB Simulink model of R – 744refrigerant loop systems

3.3.3 Refrigerant R – 152a

The performance analysis of the automotive air-conditioning system using R-152a (Figure 4) refrigerant demonstrates notable operational characteristics. Upon activation, the condensation rate peaked at 0.51 g/s, gradually decreasing and stabilizing at 0.398 g/s by 1200 seconds, reflecting steady heat exchange. As the system approached shutdown, the condensation rate dropped sharply to below 0.22 g/s when the air conditioning was turned off. In terms of power consumption, the cabin blower, radiator fan, coolant pump, and refrigerant compressor together consumed 1180 W initially, maintaining this level until around 1250 seconds. Afterward, a slight increase in power consumption was recorded, reaching 1328 W, before gradually stabilizing at 1100 W until the system was turned off at 1800 seconds. The system's average coefficient of performance (COP) was recorded at 1.94, indicating that for every unit of energy consumed, 1.94 units of cooling effect were generated. This COP reflects a slightly lower efficiency compared to other refrigerants, but the system still maintained consistent operation throughout the study period.

3.3.4 Refrigerant R-1234ze

The performance analysis of the automotive air-conditioning system using R-1234ze (Figure 4) refrigerant highlights key operational behaviors. Upon activation, the rate of condensation peaked at 0.47 g/s and gradually decreased, stabilizing at 0.39 g/s by 1200 seconds. However, when the system was turned off, the condensation rate sharply dropped to below 0.18 g/s, signaling a significant reduction in refrigerant flow. In terms of power consumption, the

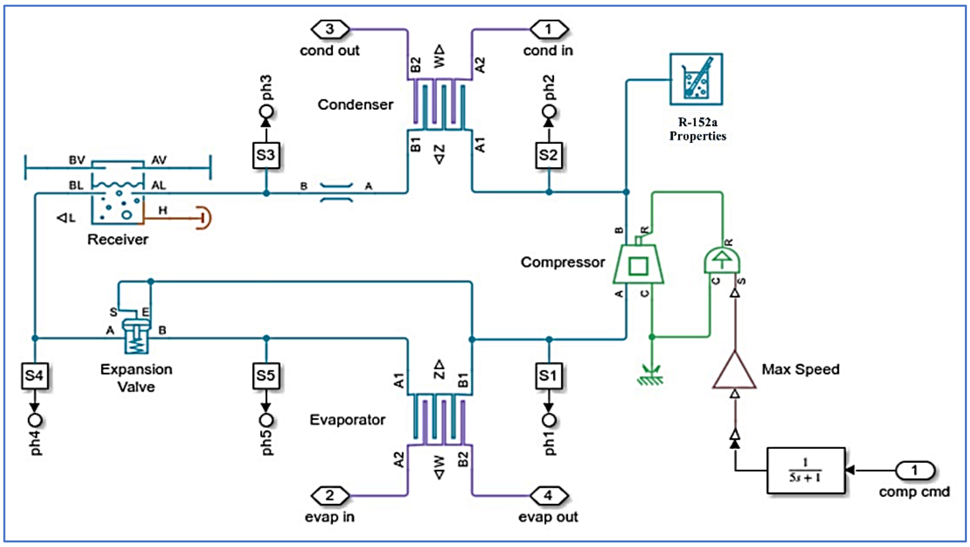

Figure 3: MATLAB Simulink model of R – 152arefrigerant loop systems

combined load from the cabin blower, radiator fan, coolant pump, and refrigerant compressor initially consumed 1110 W, maintaining this level until approximately 1250 seconds. After that, a slight decrease in power consumption was observed, bringing it down to 1090 W, before stabilizing back at 1100 W until the system was turned off at 1800 seconds. The average coefficient of performance (COP) was recorded as 2, indicating that for every unit of energy consumed, the system produced 2 units of cooling effect, reflecting balanced and efficient operation throughout the test.

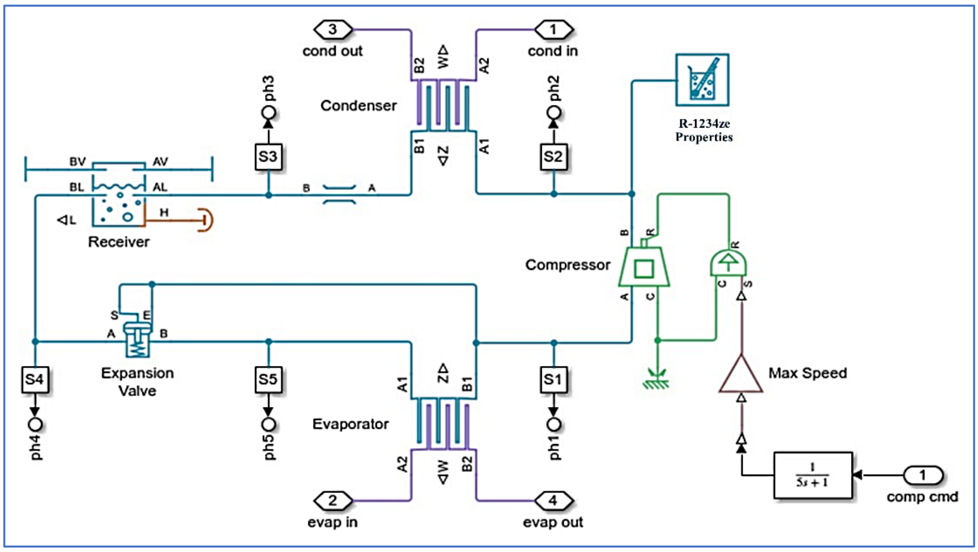

Figure 4: MATLAB Simulink model of R – 152a refrigerant loop systems

3.4 Optimization of refrigerant

The performance analysis of various refrigerants utilized in automotive air-conditioning systems highlights significant differences in efficiency and operational characteristics, ultimately leading to the conclusion that R-744 (CO_2) is the most suitable option for enhancing electric vehicle performance.Starting with R-744, the analysis shows a peak condensation rate of 0.39 g/s upon activation, which is indicative of its effective heat exchange capabilities. This refrigerant maintains a stable condensation rate of 0.33 g/s over the initial 1200 seconds of operation, demonstrating a reliable performance in maintaining thermal management. Power consumption during this period begins at a relatively low 870 W, which remains constant until about 1200 seconds, after which a slight increase in power to a peak of 1010 W is observed, primarily due to rising cooling demands. Notably, R-744 achieves an impressive average coefficient of performance (COP) of 2.41, signifying that for each unit of power consumed, the system produces 2.41 units of cooling effect. This exceptional COP not only showcases the efficiency of R-744 but also underscores its ability to effectively manage power consumption while providing adequate cooling, making it an ideal choice for electric vehicles seeking to optimize energy use.In contrast, R-1234yf exhibits solid performance characteristics, with a peak condensation rate of 0.46 g/s. The system stabilizes at a rate of 0.35 g/s after the initial activation phase. While it operates efficiently, the average COP recorded for R-1234yf is 2.1, which, although respectable, is lower than that of R-744. Power consumption starts at 1000 W, with a slight increase to 1250 W observed midway through the operation, reflecting additional cooling demands. The performance of R-1234yf is commendable, but it does not reach the same level of efficiency as R-744, indicating that while it remains a viable option, it could be enhanced further.

Similarly, R-1234ze presents a performance profile that shows a peak condensation rate of 0.47 g/s, stabilizing at 0.39 g/s after 1200 seconds of operation. It begins with a power consumption of 1110 W and experiences a slight decrease to 1090 W. The average COP for R-1234ze is recorded at 2.0, which places it in a similar category as R-1234yf, but again, it does not surpass the efficiency achieved with R-744. Both R-1234yf and R-1234ze demonstrate acceptable operational efficiency, yet they lack the superior performance metrics displayed by R-744.Finally, R-152a, while starting with the highest peak condensation rate of 0.51 g/s, shows significant inefficiencies elsewhere in its operational characteristics. The average COP of R-152a is only 1.94, indicating that it produces less cooling effect per unit of energy consumed compared to the other refrigerants discussed. Power consumption peaks at 1328 W, which is notably higher than the other refrigerants, thereby suggesting that despite its initial condensation capabilities, it is not an effective choice for energy efficiency.

The extensive analysis of the operational parameters and performance metrics of each refrigerant clearly indicates that R-744 (CO_2) stands out as the best option for improving electric vehicle performance in automotive air-conditioning systems. Its superior COP, lower power consumption, and effective condensation rates render it not only an efficient choice but also a sustainable solution for future automotive applications. As electric vehicles continue to evolve, utilizing R-744 could play a crucial role in optimizing energy consumption and enhancing overall vehicle performance, aligning with the growing need for eco-friendly technologies in the automotive sector.

4. Conclusion

1. R-744 (CO2) demonstrates the highest coefficient of performance (COP) at 2.41, indicating its superior efficiency in converting electrical energy into cooling effect compared to R-1234yf, R-1234ze, and R-152a. This efficiency highlights R-744 as the most suitable refrigerant for electric vehicles.
2. The analysis reveals that R-744 maintains lower power consumption (870 W) while providing effective cooling, unlike R-152a, which exhibits higher power consumption (peaking at 1328 W). This showcases R-744's advantage in energy management, crucial for optimizing vehicle performance.
3. R-744 achieves stable condensation rates during operation, with minimal fluctuations, enhancing the reliability of vehicle air-conditioning systems. In contrast, the other refrigerants showed more variability in their performance metrics, emphasizing the need for consistent thermal performance.
4. Employing MATLAB tools such as the Optimization Toolbox can enhance the design and analysis of air-conditioning systems by enabling simulations that refine component sizing, operating conditions, and refrigerant selection. Techniques like genetic algorithms or gradient descent can be applied to optimize system parameters, ensuring maximum efficiency and performance under varying conditions.
5. As an eco-friendly refrigerant, R-744 aligns with the global movement toward reducing greenhouse gas emissions in the automotive industry. While R-1234yf and R-1234ze offer decent performance metrics, their lower COPs (2.1 and 2.0, respectively) and higher energy demands highlight that R-744 remains the leading option for optimizing the performance of electric vehicle air-conditioning systems, balancing efficiency and environmental considerations effectively.

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