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Simulation Study on Heating Performance of Thermal Management in Heat Pump Air Conditioning Systems for Electric Vehicles

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Abstract: With the advent of the electric vehicle (EV) revolution, the market share of EVs has been steadily increasing, accompanied by growing interest in the heat pump air-conditioning system (including cooling and heating functionalities) of electric vehicles. As the second-largest energy-consuming system in a vehicle, the air-conditioning system significantly impacts driving range, especially under winter heating conditions, where excessive energy consumption can greatly reduce the vehicle's range. This study addresses the issue of high energy consumption of heat pump air-conditioning systems in winter. By constructing a one-dimensional model of the heat pump air-conditioning system for electric vehicles, the study analyzes the impact of compressor speed, EHX opening, and recirculation ratio on energy consumption and heating capacity under WLTC operating conditions at an ambient temperature of −5 °C. The results indicate that an EHX opening of 450 steps, an external air circulation ratio of 30%, and a compressor speed of approximately 5000 RPM provide optimal heating performance for the heat pump air-conditioning system. This simulation offers insights for optimizing heat pump air-conditioning systems and improving the driving range of electric vehicles. Further optimization could enhance EV range issues and boost the market competitiveness of this type of electric vehicle.

Keywords: heat pump system; thermal management; heating performance; simulation study

1. Introduction

The air conditioning system in passenger vehicles plays a crucial role not only in providing comfort but also in ensuring safety and minimizing energy consumption. This is especially important for electric vehicles (EVs), where the air conditioning system presents significant challenges in balancing comfort and driving range. Since driving range is a key factor influencing consumer acceptance of electric vehicles, attention has turned towards improving the energy efficiency of air conditioning systems to reduce the energy consumption required for cabin heating and cooling. This issue becomes even more pronounced in cold climates, where there is a high demand for heating. Unlike traditional internal combustion engine (ICE) vehicles, which can utilize engine waste heat to warm the cabin, electric vehicles must optimize their heating systems to effectively address this challenge.

Considering the global warming and CO_2 emission, more efficient engines with less waste heat is being developed. At the same time, electric vehicles (EVs) are becoming increasingly popular. This trend is raising new challenges in mobile climate control system design [1]. In cold winter conditions, traditional gasoline-powered vehicles can maintain cabin and critical component temperatures by recovering waste heat from the engine. However, to ensure passenger comfort and proper battery operation, electric vehicles, due to the relatively low waste heat generated by the motor, are unable to fully meet winter heating demands, requiring more electrical energy. This, in turn, results in further reductions in the driving range and higher carbon dioxide emissions. Moreover, since the capacity of heat pump air conditioning systems is limited, they are ineffective for heating at external temperatures below −5 °C, necessitating the introduction of PTC (Positive Temperature Coefficient) heaters, which further exacerbates the energy consumption of the system.

Comparing several mainstream refrigerants on the market, including R134a, R1234yf, R407C, and R410a, it is observed that the cooling capacity and COP values of R134a and R1234yf are similar but higher than those of the other two refrigerants. Due to the lower ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) of R1234yf compared to R134a, R1234yf can be considered a viable alternative to R134a in the future. However, the significantly lower usage cost of R134a remains the primary barrier to the widespread adoption of R1234yf. Under identical conditions, air-conditioning systems using R407C exhibit higher overall energy consumption than those utilizing R134a or R1234yf. Meanwhile, systems using R410a as the refrigerant demonstrate significantly lower COP compared to the other three refrigerants. Therefore, based on a comprehensive evaluation, this study focuses on the investigation of heat pump air-conditioning systems using R134a as the working fluid.

Some research results have been achieved regarding heat pump air-conditioning systems for heating purposes. Meyer and Yang et al. [2], recognizing the challenge posed by enhanced engine efficiency leading to insufficient heat from coolant water for winter cabin heating, developed an R134a-based heat pump air-conditioning system that harnesses the engine's coolant as its heat source. Rigorous testing revealed remarkable performance, with a Coefficient of Performance (COP) surpassing 2.0 and a heating capacity exceeding 6.0 kilowatts, showcasing a significant advancement in efficient heating solutions.

In 2014, Li et al. [3] devised a hybrid air-source heat pump air-conditioning system tailored for battery electric vehicles (BEVs). Simulation outcomes indicated that this system effectively mitigates the issues encountered by conventional non-hybrid BEV heat pump systems under low-temperature conditions, namely elevated compressor discharge temperatures and severe degradation in heating performance. This innovation represents a notable step forward in addressing the thermal management challenges faced by BEVs.

Pan et al. [4] and his colleagues from Shanghai Jiao Tong University conducted a study on the energy-saving potential of automotive air-conditioning systems through the utilization of recirculated air. Their findings revealed that the PTC heating system, when employing recirculated air, could achieve a notable energy savings of 14% to 16% in heating operations, underscoring the significant potential for energy efficiency enhancement in automotive thermal management systems.

An integrated thermal management system (VITMS) of hydrogen fuel cell vehicle (FCV) based on heat pump air conditioning is proposed by Qu et al. [5] to solve the issues of poor temperature control and high energy consumption in current dispersed TMS. The VITMS has excellent thermal control performance and can realize fourteen work modes such as cooling, heating, preheating, defrosting and energy recovery, ensuring the optimal temperature ranges and temperature uniformity of fuel cell, power battery, motor, and cabin.

Peng and Du et al. [6] presented a review of alternative environmentally friendly refrigerants in electric vehicles, discussing numerous advanced technologies. They reviewed innovations such as inverter technology, innovative components, and the system architecture of heat pump air conditioning systems for electric vehicles. The latest developments in multi-source heat pump systems were also introduced. The use of these advanced technologies not only provides sufficient cooling capacity for electric vehicles but also enhances the efficiency of climate control systems.

Zou et al. [7] investigated the heating performance of a test system under the influence of expansion valve (EXV) opening and operating conditions. It was found that increasing the EXV opening could improve heating performance to some extent. Their experimental results showed that, at 5000 RPM, as the ambient temperature decreased from 0°C to -10°C, the heating capacity of the R1234yf heat pump system decreased by approximately 37.2%. Therefore, it is essential to optimize the operation of the heat pump and PTC heater based on integrated efficiency.

Qin et al. [8] building on traditional PID control and fuzzy PID control strategies, proposed a control system that uses a WOA-PID (Whale Optimization Algorithm) fuzzy control strategy to adjust the compressor speed, thereby achieving optimal cabin temperature control. These improvements optimized the system by reducing overshoot and settling time, effectively enhancing the heating performance of the system.

In the present paper. A one-dimensional heating model of the heat pump air conditioning system has been established using Amesim, to investigate the impacts of expansion valve opening, compressor speed, cycle ratio, and refrigerant charge amount on the heating performance.

2. Development of a One-Dimensional Model

Figure 1 illustrates the schematic diagram of the heat pump air-conditioning system, which consists of compressors, condensers, throttling devices, evaporators, and other essential components. In heating mode, the refrigerant is compressed into a high-temperature, high-pressure gas by the compressor. This gas then flows through the four-way valve into the indoor heat exchanger, where it releases heat and condenses into a subcooled liquid. The liquid then passes through the throttling device, becoming a low-temperature, medium-pressure two-phase fluid via the expansion valve. It subsequently enters the outdoor heat exchanger, where it evaporates and absorbs heat. Upon completing this cycle, the refrigerant returns to the compressor through the receiver to initiate a new cycle. In this process, the indoor heat exchanger functions as the condenser, while the outdoor heat exchanger acts as the evaporator.

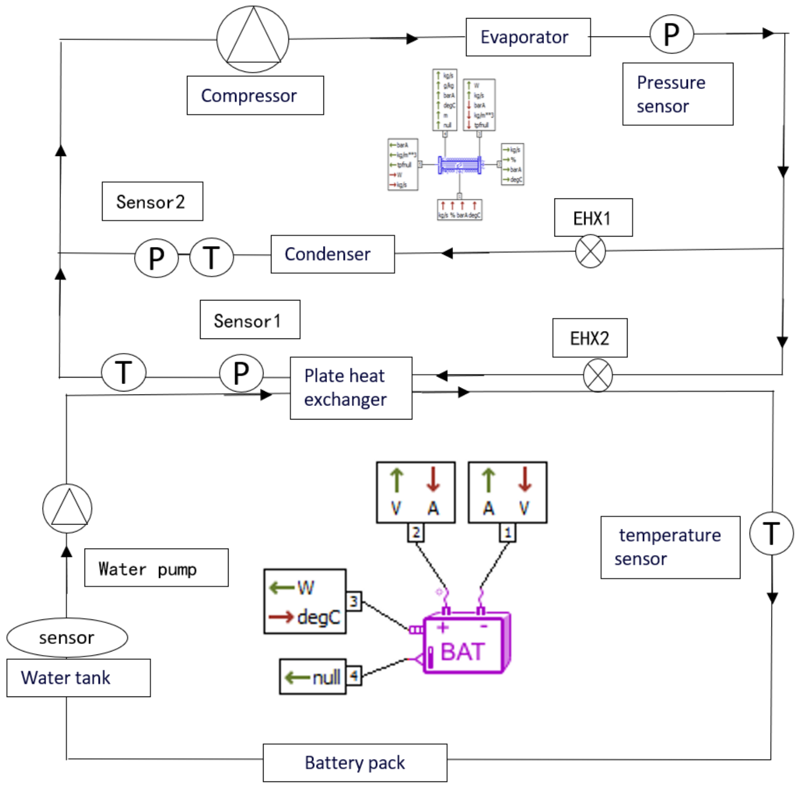

Figure 1. Schematic diagram of the heat pump system..

The heat pump air-conditioning system model is depicted in Figure 2, where the wet air outlet of the condenser is directed towards the passenger cabin in heating mode. Most of the parameters of the thermal management system model can be adjusted based on the actual component specifications. Furthermore, simulations can be conducted by varying operational conditions, such as ambient temperature, humidity, and illumination, to meet different requirements.

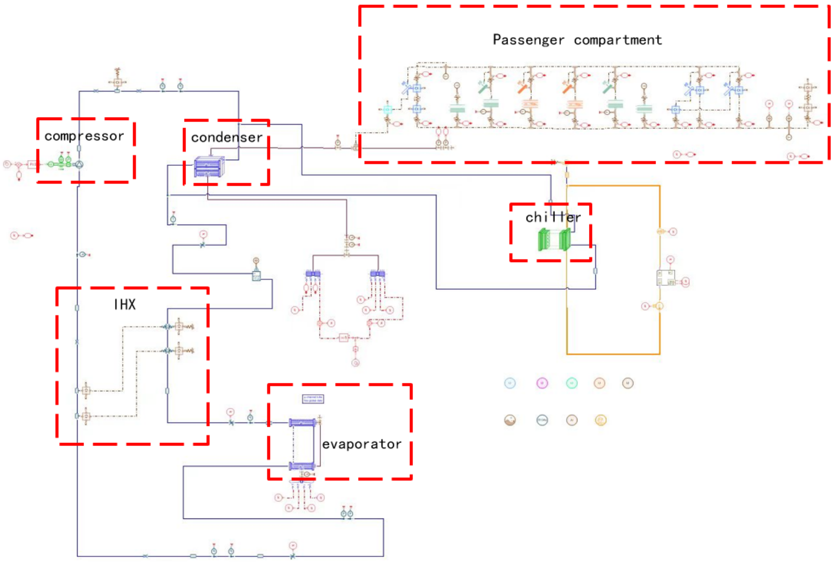

Figure 2. One-dimensional model for heat pump air conditioner heating..

3. Results and Discussions

3.1. The Impact of the Expansion Valve Opening Degree

3.1.1. The Effect of Electronic Expansion Valve Opening on Exhaust Temperature

To meet the heating demands of the passenger cabin in a low-temperature environment of −5 °C, the compressor must operate at relatively high speeds. If the expansion valve (EXV) opening is too small during this operation, it may cause the temperature and pressure within the compressor to exceed safe limits. To analyze the impact of the EXV opening, simulations were conducted at compressor speeds of 4000 rpm, 5000 rpm, and 6000 rpm, as shown in Figure 3, with the valve opening varying from 50 to 500 steps. Due to the significant pressure differential, a minimal opening of the expansion valve can result in compressor temperatures and pressures surpassing their theoretical limits (exceeding 150 °C). Such conditions are unsuitable for practical applications, as high temperatures may lead to detrimental reactions, such as the carbonization of lubricating oil, which would adversely affect the compressor's lifespan and could even lead to compressor failure. When the expansion valve opening is at least 150 steps, the discharge temperature can be maintained below 100 °C, significantly reducing the risk of high temperatures and preventing the equipment from operating under extreme conditions.

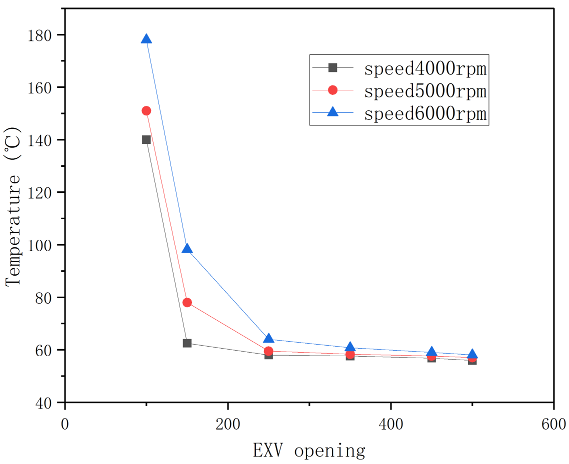

Figure 3. Impact of Different Expansion Valve Openings on Exhaust Performance..

3.1.2. The Impact of Expansion Valve Opening on Heating Capacity and Power Consumption

At an ambient temperature of −5 °C and a corresponding air inlet temperature, the heating capacity of the heat pump system decreases as the expansion valve opening increases. As shown in Figure 4, an increase in the expansion valve opening leads to a rapid decline in the compressor's discharge temperature and pressure, resulting in a significant reduction in the temperature difference inside the vehicle and, consequently, a decrease in heating capacity. Additionally, the sharp drop in discharge pressure, combined with the relatively stable suction pressure influenced by the external temperature, causes a significant reduction in the compression ratio. This results in decreased work done by the compressor, further impacting the heating effect. This decline in heating capacity becomes more pronounced at higher speeds. When the expansion valve opening is reduced, the system's input power increases from 1643 W to 2134 W at 4000 rpm, from 1867 W to 2834 W at 5000 rpm, and from 2485 W to 3875 W at 6000 rpm. The coefficient of performance (COP) of the heat pump system reflects its overall operational efficiency, directly affecting the winter driving range of electric vehicles. Figure 4 shows that at 4000 rpm, with a 450-step opening, the COP reaches its highest value of 3.26. While at 5000 rpm the maximum COP values are 2.7 and minimum are 2.52. At 6000 rpm, the maximum COP values are 2.03 and the minimum are 1.89.

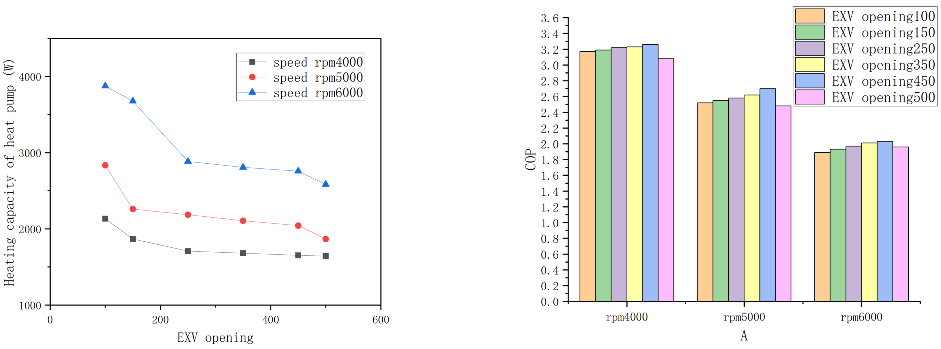

Figure 4. Heating capacity and COP at different EXV openings..

3.2. The Impact of Different Cycle Ratios on Heat Pump Air Conditioning Performance

In heating mode, the air-conditioning system of a vehicle utilizes the recirculation mode to rapidly increase the cabin temperature. However, continuous operation in recirculation mode causes a rapid increase in the concentration of carbon dioxide (CO_2) within the cabin and a gradual decrease in oxygen levels. This can impair the driver's ability to focus, potentially increasing the probability of accidents over extended periods. Additionally, prolonged exposure to an environment with low oxygen levels (i.e., CO_2 concentration exceeding 0.15%) can have adverse health effects. Therefore, the air-conditioning system must periodically draw in fresh air from the outside to ensure safe driving while reducing the concentration of harmful gases inside the cabin.

This section primarily analyzes the effects of different recirculation ratios on the temperature and humidity within the passenger cabin. The study assumes the following outdoor environmental conditions: an ambient temperature of −5 °C, relative humidity of 40%, and a target cabin temperature of 22 °C under WLTC operating conditions.

Figure 5 illustrates the variation in heating capacity of the air-conditioning system with different recirculation ratios. As the proportion of external air increases, the heating capacity of the air-conditioning system also increases correspondingly. Notably, when the system operates entirely in recirculation mode, the heating capacity reaches its lowest point, but the heating efficiency is at its peak. This is because the system primarily recirculates cabin air, minimizing heat loss to the external environment.

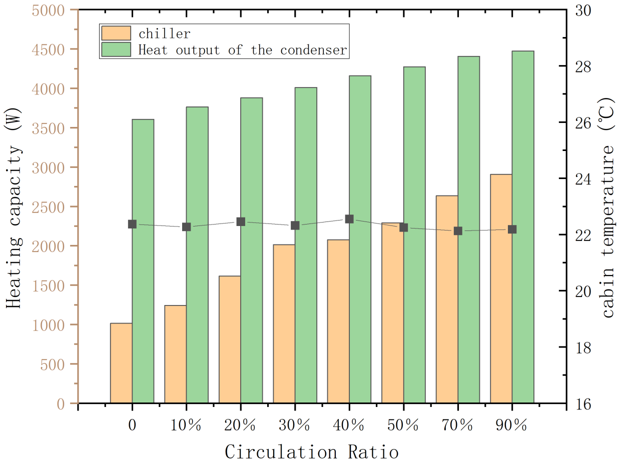

Figure 5. Heating capacity of heat pump systems under different heating cycle ratios..

Adjusting the ratio of fresh air to recirculated air requires the system to consume additional energy to heat the incoming fresh air, enabling a rapid increase in cabin temperature. This leads to an overall increase in heating capacity. When the proportion of external air exceeds 50%, the growth rate of heating demand begins to slow. Compared to the fully recirculation mode, the heating capacity increases by 44.08% at this point. Further adjustments to the ratio of fresh air and recirculated air result in a continued rise in heating capacity. Under fully external air mode, the heating capacity increases by 1.62 times compared to the fully recirculation mode.

3.3. The Impact of Compressor Speed on Heat Pump Air Conditioning Performance

This section primarily investigates the influence of compressor speed on key parameters of the heat pump air-conditioning system. The compressor speed is set within a range of 2000–7000 RPM. Simulation tests of the heat pump air-conditioning system's heating performance are conducted under the following conditions: an ambient temperature of −5 °C, a flow rate of 5 L/min at the inlet of the battery liquid thermal plate, a fixed expansion valve opening, and a fresh air-to-recirculated air ratio of 30%.

As shown in Figure 6, the performance of the air-conditioning system varies significantly with different compressor speeds. At a compressor speed of 2000 RPM, the heating output of the system is relatively low, with the condenser providing 805.91 W and the chiller reaching 2395 W. The coefficient of performance (COP) at this setting peaks at 3.57.

As the compressor speed increases, the heating output of the air-conditioning system rises substantially, while the COP exhibits a downward trend. When the compressor speed is raised to 7000 RPM, the condenser's heating output increases to 2875.62 W, and the chiller's output reaches 3937.24 W, representing approximately a 2.13-fold increase compared to the 2000 RPM setting. This enhancement is primarily due to the increased compressor speed, which allows more refrigerant to circulate within the system, thereby boosting its heating capacity.

The energy consumption of the compressor also rises dramatically, increasing by about 4.33 times compared to the 2000 RPM condition. This rapid escalation in energy use leads to a significant drop in COP, from 3.56 to 1.74, a reduction of 49.05%.

The data also reveals a discernible pattern in the impact of compressor speed on system COP. At lower speeds, the COP declines rapidly, but this effect diminishes as the speed increases. This underscores the necessity of balancing heating output and COP when designing and operating air-conditioning systems to achieve optimal energy efficiency.

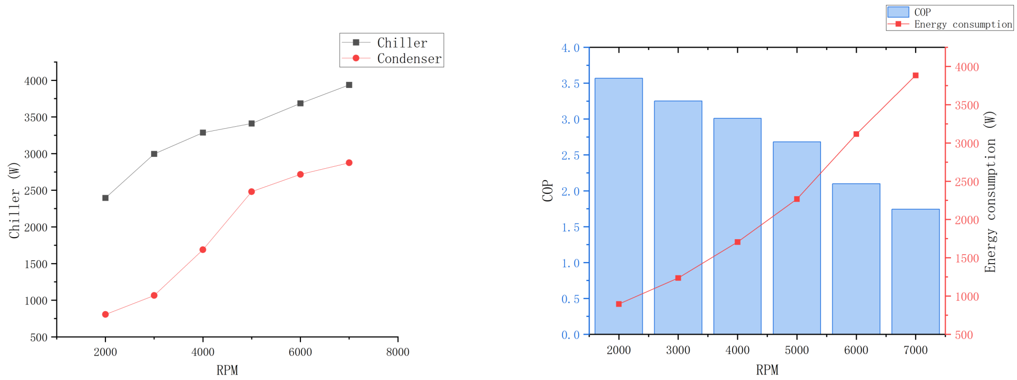

Figure 6. Cooling Capacity and COP of the Heat Pump System at Different Compressor Speeds..

4. Conclusion

This study primarily utilizes the one-dimensional simulation software Amesim to develop a model of a heat pump air conditioning system. It analyzes and compares the effects of varying compressor speeds, circulation ratios, and electronic expansion valve (EXV) openings on the system's performance. The findings indicate that:

(1) With variations in compressor speed, the system achieves the maximum COP when the expansion valve (EXV) opening is set to 450 steps. At 4000 RPM, the COP reaches its peak value of 3.26, while at 5000 RPM and 6000 RPM, the COP decreases to 2.7 and 2.03, respectively. The EXV opening significantly impacts the condensation conditions but has minimal effect on evaporation conditions and compressor inlet conditions. To some extent, increasing the EXV opening is beneficial for improving heating performance.

(2) As the compressor speed increases, the condensation pressure rises, the evaporation pressure decreases, and both compressor energy consumption and heating capacity increase to varying degrees, resulting in a decline in COP. At 7000 RPM, compared to 2000 RPM, the heating capacity increases by 2.13 times, while energy consumption increases by 4.33 times. Therefore, in practical applications, excessively high compressor speeds should be avoided.

(3) Reducing the proportion of external air circulation effectively improves the heating efficiency of the heat pump air-conditioning system. However, this reduction leads to a rapid increase in cabin CO_2 concentration, negatively impacting cabin comfort and potentially creating safety hazards for drivers. Thus, in practical applications, a reasonable ratio of fresh air to recirculated air should be maintained, with an external air circulation proportion of 30% being optimal.

(4) Due to the significant decline in COP at low ambient temperatures and high compressor speeds, it is crucial to identify the optimal operating mode for the heat pump system. Supplementing the system with a PTC heater is recommended to ensure better heating performance.

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Conflicts of Interest: The author declares no conflict of interest.

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