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Thermodynamics-Based Energy Management Strategy for Electric Vehicle Braking

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ABSTRACT

With the intensifying global energy crisis and environmental issues, electric vehicles (EVs) have emerged as a crucial direction for future transportation development due to their high efficiency and zero emissions. However, EVs still face numerous technical challenges in practical use, particularly in braking energy management and thermal management system optimization. This paper aims to deeply analyze the regenerative braking process of EVs based on the second law of thermodynamics to uncover the irreversible losses and optimization pathways in energy conversion. Furthermore, a comprehensive vehicle thermal management system model is established, with detailed parameter settings and optimization to ensure efficient operation under various conditions. The research results indicate that the thermodynamics-based braking energy management strategy can significantly enhance the energy efficiency and range of EVs. Additionally, optimizing the vehicle's thermal management system contributes to improving overall vehicle performance and reliability.

1. INTRODUCTION

With the intensifying global energy crisis and environmental issues, EVs are gradually becoming the direction for future transportation development due to their zero emissions and high efficiency characteristics [1-3]. However, EVs still face many technical challenges in practical use, including how to effectively manage regenerative braking energy and optimize the vehicle's thermal management system [4]. Regenerative braking energy not only affects the driving range of EVs but also has a significant impact on the vehicle's thermal management and overall energy efficiency [5]. Therefore, researching how to optimize the braking energy management strategy of EVs based on the second law of thermodynamics to improve energy utilization efficiency is a topic of great practical significance.

Relevant studies have shown that a reasonable braking energy management strategy can not only significantly increase the driving range of EVs but also reduce energy waste and lower the thermal load on the battery and other key components, thereby extending their service life [6-8]. The second law of thermodynamics, as a fundamental law of energy conversion and transfer in nature, provides a theoretical basis for the optimization of braking energy management strategies. By applying the second law of thermodynamics to the regenerative braking process, we can more accurately analyze the flow and loss of energy, thereby formulating a more efficient energy management plan [9, 10]. This not only has a positive significance for the economy and environmental protection of EVs but also provides reliable technical support for the development of future intelligent transportation systems.

However, existing research methods still have some shortcomings in dealing with EV regenerative braking energy and thermal management systems. Many studies rely too much on empirical formulas and simplified models, ignoring the impact of irreversible losses in the energy transfer process, resulting in energy management strategies that cannot achieve optimal results [11-15]. In addition, traditional thermal management system models often lack the ability to respond to real-time dynamic environments and cannot effectively cope with complex actual conditions. These defects and shortcomings limit the performance of EVs in practical applications and urgently need to be improved through new research methods [16-19].

This paper aims to fill the gaps in existing research through two main parts. First, we will deeply analyze the regenerative braking process of EVs based on the second law of thermodynamics to reveal the irreversible losses and optimization pathways in energy conversion. Second, based on the results of the previous analysis, a comprehensive vehicle thermal management system model will be established, with parameter settings and optimization to ensure efficient operation under various conditions. Through these studies, we not only provide new theoretical support for EV energy management strategies but also hope to improve the energy efficiency and reliability of the entire vehicle, which has important academic and practical value for promoting the development of EV technology.

2. ANALYSIS OF EV REGENERATIVE BRAKING BASED ON THE SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics states that in any spontaneous process, the entropy of an isolated system always increases, while the total energy of the system remains unchanged. In a traditional braking system, the kinetic energy of the vehicle is converted into heat energy through friction and dissipated into the environment, which obviously increases the entropy of the environment. In the regenerative braking system of EVs, part of the kinetic energy is recovered and converted into electrical energy stored in the battery, thereby reducing the heat dissipated into the environment. This process does not violate the second law of thermodynamics because, although the entropy of the system decreases, the process is not an isolated system and exchanges energy with the outside world. The recovered electrical energy can be further used to drive the vehicle, thereby improving energy utilization efficiency. Figure 1 shows the thermal management system of the EV regenerative braking.

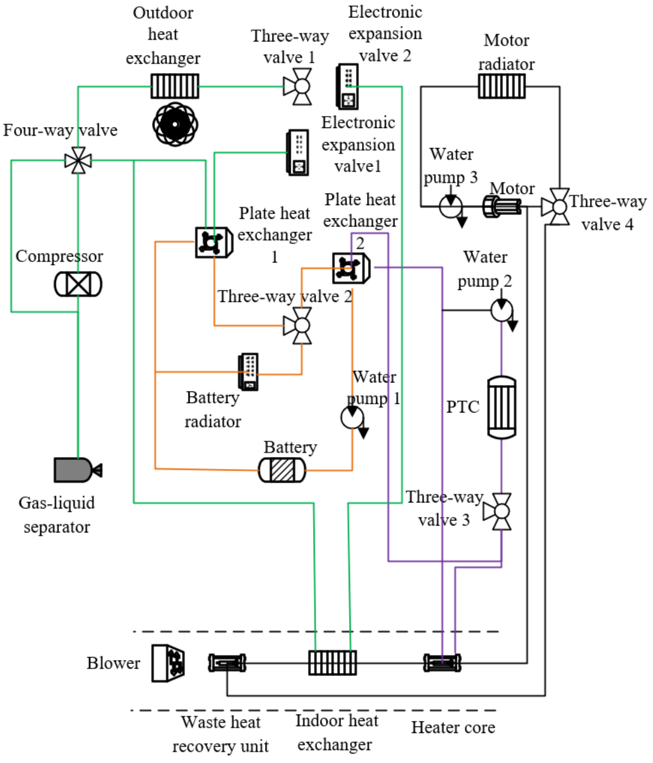


Figure 1. Thermal management system of the EV regenerative braking

The energy consumption calculation method for EVs based on the second law of thermodynamics mainly focuses on the energy conversion efficiency of the system and the energy loss in irreversible processes. During the calculation, energy consumption considers not only the alternating current input from the power grid or the high-voltage direct current output from the power battery but also the inevitable entropy increase and energy loss during the entire energy conversion process. According to the second law of thermodynamics, any actual energy conversion process will produce an entropy increase, causing part of the energy to dissipate as heat and not be fully converted into useful work. Therefore, when calculating energy consumption, these energy losses should be quantified. Specifically, to complete the calculation, it is necessary to measure and analyze the energy input and output of EVs under different operating conditions, such as driving, acceleration, deceleration, and braking, as well as the energy conversion efficiency of each link.

In the experiment, the output high-voltage direct current from the power battery should be taken as the starting point, covering the energy stored after the battery pack is fully charged and the part of the energy recovered from braking. To accurately evaluate energy flow, the experiment must monitor the electrical energy output from the battery and analyze it using the vehicle energy flow simulation model built with AMEsim software. Based on this, the efficiency of the charger, energy loss during the charging process, energy conversion efficiency of the motor and control system during vehicle operation, and energy loss in the thermal management system should be considered. The specific experimental approach includes several key steps. First, simulate and measure the energy output of the battery under different operating conditions, such as constant speed driving, acceleration, deceleration, and braking. Second, accurately record and analyze the efficiency of the regenerative braking system, quantifying the difference between the recovered energy and the actual utilized energy. Third, evaluate the irreversible losses in the entire energy conversion process, especially the heat energy dissipation caused by entropy increase. By comprehensively considering these factors, the experiment can more accurately reflect the actual energy consumption situation.

The energy flow study of EVs based on the second law of thermodynamics conducted in this paper comprehensively considers the energy conversion and loss in the power transmission system and the thermal management system. The power battery, as an energy source, distributes electrical energy to system components such as the air conditioner, motor, and DC/DC converter through the high-voltage power distributor. The DC/DC converter converts high-voltage electrical energy into low-voltage electrical energy, supplying the low-voltage battery to provide an energy source for low-voltage accessories. When the vehicle brakes, the kinetic energy generated by the wheels is converted into electrical energy through the inverter and sent back to the power battery, achieving regenerative braking. During the discharge process of the power battery, the internal resistance loss and discharge efficiency of the battery must be considered; when the high-voltage power distributor distributes electrical energy, the conversion efficiency and thermal loss of the distributor must be considered; the energy conversion of the motor and DC/DC converter also involves electromagnetic losses and thermal losses. In addition, the low-voltage battery also has energy losses during the charge and discharge process. The energy flow of the thermal management system cannot be ignored either. The energy consumption of the air conditioning system mainly includes the electrical energy consumption of the compressor and the thermal loss in the cooling cycle. During the entire vehicle operation, the motor and electronic components generate heat, which is dissipated through the cooling system, representing a part of the energy loss that cannot be used for driving.

Calculating the energy consumption ratio and operating efficiency of each key component based on the second law of thermodynamics is crucial for optimizing the energy management strategy of EVs. In the analysis of the vehicle energy flow, it is first necessary to identify and monitor the energy input and output of key components. Through detailed energy flow data, the energy consumption ratio and operating efficiency of each component under different operating conditions and temperature conditions can be calculated. Combined with the second law of thermodynamics, the irreversible losses and entropy increase phenomena in the entire energy transfer process are analyzed, clearly identifying the sources of inevitable energy losses in each link. By analyzing the energy consumption distribution and ratio under different conditions and temperatures, it is possible to identify under what conditions the energy loss is the greatest and which components have the most potential for efficiency improvement. Finally, by analyzing the energy flow during braking, the efficiency of regenerative braking and the proportion of actually recovered energy can be calculated. Understanding the performance of the energy recovery system under different operating conditions can help optimize the regenerative braking energy management strategy and improve recovery efficiency.

Assuming the energy ratio is represented by ψ, the cumulative energy loss and regeneration of the system or component is represented by R_0, and the total output energy of the power battery is represented by R_{ZSC}, the calculation formula for the energy ratio is:

$$\psi = \frac{R_0}{R_{ZSC}} \times 100\% \tag{1}$$

Assuming the braking energy recovery rate is represented by v_{HS}, the energy recovered by the power battery is represented by R_{HS}, and the energy recoverable by the wheels during braking is represented by R_{BR}, the calculation formula for the EV braking energy recovery rate is:

$$v_{RE} = \frac{R_{HS}}{R_{BR}} \times 100\% \tag{2}$$

3. MODEL AND PARAMETER SETTING OF THE THERMAL MANAGEMENT SYSTEM FOR EVS

The thermal management system of EVs includes multiple subsystem circuits, such as the battery cooling circuit, motor cooling circuit, and air conditioning system. However, in considering the thermal management system model of regenerative braking, special attention must be paid to the thermal effects generated during the regenerative braking process. For example, when the vehicle performs regenerative braking, the motor converts kinetic energy into electrical energy and feeds part of the electrical energy back to the battery system. During this process, the operation of the motor and inverter generates heat, which needs to be dissipated through the motor cooling circuit. The battery also generates a certain amount of heat when receiving the feedback electrical energy, so the parameter setting of the battery cooling system needs to consider these thermal loads. Specifically, in the modeling process, the parameter settings of key components such as the cooling pump, radiator, cooling pipes, and heat exchanger are crucial. These parameter settings can refer to the data provided by manufacturers and actual test data, such as the flow and pressure characteristics of the cooling pump, the thermal conductivity and cooling capacity of the radiator, and the flow and temperature of the coolant. Additionally, some parameters that are difficult to obtain can be set by referring to the demo in AMEsim software to ensure the accuracy and reliability of the model.

(1) Drive System Cooling Circuit

In the context of regenerative braking, the drive system cooling circuit mainly includes modules such as the front and rear motors and motor controllers, electronic water pumps, radiators, electromagnetic three-way and four-way valves, expansion water tanks, and cooling pipes. As the core component of coolant circulation, the model of the electronic water pump needs to accurately describe the pump's flow characteristics, pressure characteristics, and power consumption characteristics. Through precise control of the electronic water pump, the flow rate of the coolant in the system can be adjusted to meet different thermal load requirements, especially during regenerative braking when the motor and motor controller generate additional heat. The performance parameters of the water pump must ensure timely heat dissipation. The radiator model needs to focus on its thermal conductivity and cooling capacity. The radiator maintains the normal temperature of the drive system through heat exchange between the coolant and the outside air. In the context of regenerative braking, the radiator must be able to handle additional heat to prevent the system from overheating. The design and parameter setting of the radiator should also be based on actual working conditions and experimental data to ensure efficient heat dissipation. Electromagnetic valves play a role in switching flow paths in the cooling circuit, and their models must accurately describe the valve switching speed, flow control, and response time. Through intelligent control of the electromagnetic valves, quick switching of the coolant between different circuits can be achieved, optimizing the thermal management strategy. In addition, the coolant flowing in the cooling pipes is usually an ethylene glycol aqueous solution mixed in a 50%:50% ratio. The ethylene glycol aqueous solution has good thermal conductivity and antifreeze properties, suitable for the cooling needs of EVs. The thermal physical parameters of the fluid, such as density, specific heat capacity, and thermal conductivity, need to be accurately reflected in the model to precisely calculate the heat conduction and convection processes of the coolant. Below, the modeling process of each module is detailed.

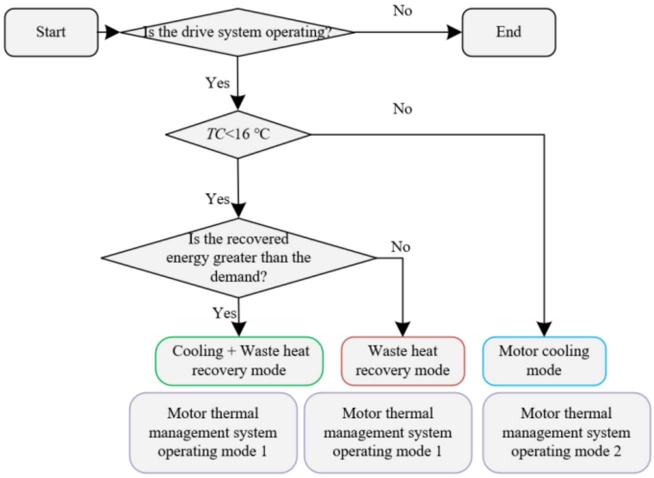


Figure 2. Control strategy for the drive system thermal management system

Figure 2 shows the control strategy for the drive system thermal management system. During regenerative braking, the motor and motor controller generate additional heat, requiring the pump to operate in high-efficiency mode to ensure that the coolant can quickly remove the excess heat and prevent the system from overheating. For the electronic water pump, a rule-based control method is adopted in this paper, and a centrifugal pump is selected as the electronic water pump model in AMEsim software. The rotational speed and torque information are transmitted through interface 1, while interfaces 2 and 3 are responsible for the input and output of signals such as flow rate, pressure loss, and temperature. Through interpolation calculations of the pump performance test data, the relationship between the pressure loss and flow rate of the pump at the reference speed can be obtained, ensuring that the pump can adjust its working state according to real-time needs to optimize the system's thermal management. Assuming the input pressure is represented by po_{SR}, the pressure difference by Δo, the volumetric flow rate of the pump by W, and the overall efficiency by v_{EFF}, the output pressure o_{SC} of the pump can be calculated by the following formula:

$$o_{SC} = o_{SR} + \Delta o \tag{3}$$

The power O_{ME} provided by the pump to the fluid can be calculated by the following formula:

$$O_{ME} = W \cdot \Delta o / v_{EFF} \tag{4}$$

$$0 \le v_{EFF} \le 1 \tag{5}$$

During regenerative braking, the drive system generates a large amount of heat, which, if not dissipated in time, will increase the thermal load of the cooling circuit. To ensure the thermal balance of the system, the radiator must operate efficiently, not only dissipating excess heat in time but also maintaining stable performance under various working conditions. This requires the radiator model to accurately simulate the heat exchange process between the coolant and the air and dynamically adjust according to real-time air temperature, wind speed, and coolant flow rate. In addition, the radiator model must consider the role of the fan, as the airflow from the fan directly affects the heat exchange efficiency of the radiator. During regenerative braking, the fan needs to start and adjust the wind speed in time according to the cooling needs to maximize the cooling effect. This process requires the model to effectively combine the control signals of the fan and the actual working conditions, ensuring rapid heat dissipation under high thermal load conditions to prevent the coolant temperature from being too high. For this purpose, an integrated fan radiator model in AMEsim software is selected in this paper. This model interacts with the system through multiple interfaces: interface 1 provides information on the inlet air temperature and wind speed of the radiator, interface 2 connects the expansion water tank, the coolant enters the radiator from interface 3 and exits from interface 5, while the fan airflow is driven by the signal input from interface 4. Assuming the heat exchange amount of the radiator is represented by D, the air velocity by n, and the volumetric flow rate of the coolant by wmg, the heat exchange amount between the coolant and the air passing through the radiator is defined by the following formula:

$$D = d\left(n, wmg\right) \tag{6}$$

The projected area of the fan on the radiator determines the air velocity through the radiator. This velocity is one of the key variables of air flow rate and cooling effect. By calculating the ventilation area, we can determine the air velocity, thus estimating the heat exchange through this ventilation area. Assuming the air velocity at the radiator inlet is represented by N_e, and the additional velocity when the fan is running is represented by N_d, the air velocity through the radiator ventilation area VN is:

$$N = N_e + N_d \tag{7}$$

The heat exchange area in the radiator can be divided into ventilated and non-ventilated areas. The heat exchange amount in the ventilated area is the heat taken away by the air guided by the fan through the radiator, and this part of the heat exchange amount is closely related to the air velocity. The heat exchange amount in the non-ventilated area mainly relies on natural convection and radiation for cooling, and the efficiency of this part is relatively low. The calculation formula of the ventilation area X_0 is:

$$X_0 = \left(F_{WJ}^2 - F_{NJ}^2\right)\pi/4 \tag{8}$$

In general, the total heat exchange amount of the radiator is the sum of the heat exchange amounts in the ventilated and non-ventilated areas. However, the actual heat exchange amount must also consider the actual working conditions and thermodynamic efficiency of the system. Based on the second law of thermodynamics, the model needs to consider irreversible processes and system energy losses. Therefore, the actual heat exchange amount *Hreal* depends not only on the theoretically calculated total heat exchange amount but also needs to correct the heat loss and efficiency issues under actual working conditions. Assuming the outer diameter of the fan is represented by F_{WJ}, the inner diameter of the fan by F_{NJ}, the height of the radiator by g, the length of the radiator by m, the surface efficiency of the radiator by λ, the actual temperature of the coolant input to interface 3 of the radiator model by S_Z, and the actual temperature of the air input to interface 1 of the radiator model by S_e. The heat exchange amount $G1$ in the ventilation area of the radiator can be calculated by the following formula:

$$G_1 = d\left(V, wmg\right) \times X_0 / \left(g \times m\right) \tag{9}$$

The non-ventilated area X_1 of the radiator can be calculated by the following formula:

$$X_1 = g \times m - X_0 \tag{10}$$

The heat exchange amount G_2 in the non-ventilated area can be calculated by the following formula:

$$G_2 = d\left(N_e, wmg\right) \times \left(g \times m - X_0\right) / \left(g \times m\right) \tag{11}$$

Combining the above two formulas, the total heat exchange amount G of the radiator can be calculated by the following formula:

$$G = G_1 + G_2 \tag{12}$$

During regenerative braking, the drive system of EVs generates additional heat, increasing the thermal load on the cooling system. Therefore, the integrated fan radiator model must be able to dynamically adjust to adapt to this change. The speed of the fan and the ventilation area need to be adjusted in real-time according to the cooling needs to maximize the cooling efficiency. In addition, the model should accurately simulate the relationship between air velocity and coolant flow rate under different working conditions, ensuring efficient cooling even under high thermal load conditions. Therefore, the actual heat exchange amount G_{SJ} of the heat exchanger can be calculated by the following formula:

$$G_{SJ} = d(G) \times \lambda \times (S_Z - S_e) / \Delta S \tag{13}$$

Considering the context of regenerative braking, the three-way valve optimizes the circulation path of the coolant, reducing irreversible losses during heat transfer and improving the overall thermal efficiency of the system. The four-way valve intelligently adjusts the series-parallel mode of the cooling circuit, ensuring that the system can manage heat in the most efficient way under various working conditions, especially under high thermal loads. The control model of these valves needs to pay special attention to the dynamic response and flexibility of the system. The three-way and four-way valves not only need to monitor the coolant temperature in real-time but also respond quickly to temperature changes, adjusting the circulation path and circuit connection mode to meet instantaneous thermal management needs.

(2) Power Battery Thermal Management Circuit and Air Conditioning System Circuit

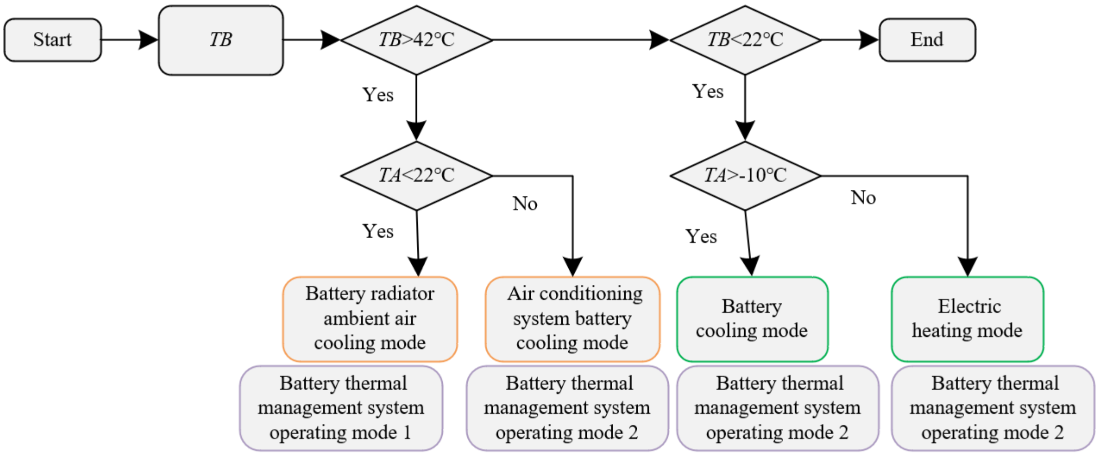


Figure 3. Control strategy for the power battery thermal management system

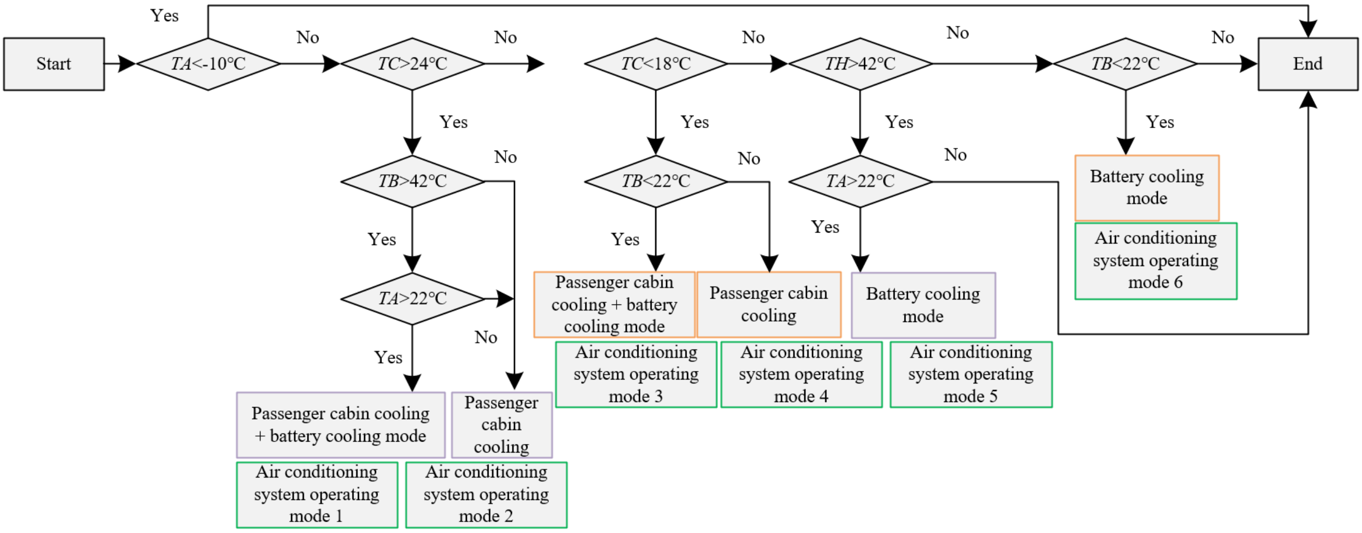


Figure 4. Air conditioning system control strategy

During regenerative braking, the power battery and other electronic components generate a large amount of heat that needs to be dissipated quickly through efficient heat exchangers to maintain stable system operation. In this context, the coordinated control of the power battery thermal management circuit and the air conditioning system circuit is particularly important. The power battery thermal management circuit mainly includes the power battery, electronic water pump, PTC water heater, and chiller. The electronic water pump and PTC water heater need to dynamically adjust the flow rate and heating power based on real-time temperature and thermal load to ensure that the power battery maintains an appropriate operating temperature under different conditions. During the cooling process, the chiller, in cooperation with the evaporator and condenser in the air conditioning system, can effectively transfer heat from the power battery and other high-temperature components. The air conditioning system circuit includes the electric compressor, expansion valve, evaporator, condenser, and passenger cabin. These components need to consider passenger comfort while providing efficient cooling. The extra heat generated during regenerative braking needs to be effectively dissipated through these heat exchangers to avoid overheating and affecting system performance and safety. Figure 3 shows the control strategy for the power battery thermal management system. Figure 4 shows the control strategy for the air conditioning system.

Based on the second law of thermodynamics, the design of the heat exchanger model needs to minimize irreversible losses and improve energy efficiency. To achieve this goal, the heat exchange efficiency of the chiller must be optimized. The flow channel design, heat exchange area, and material selection on the coolant side and refrigerant side all need to be considered to ensure that heat can be transferred quickly and efficiently. Especially during regenerative braking, the system's thermal load changes significantly, making the dynamic response capability of the chiller particularly important. Additionally, in the entire thermal management system, the coordination between the chiller and other heat exchangers (such as the evaporator and condenser) is also crucial. The evaporator is responsible for absorbing heat from the passenger cabin, causing the refrigerant to evaporate and absorb heat, while the condenser releases the refrigerant's heat to the external environment. During regenerative braking, the chiller works in conjunction with these heat exchangers to ensure that the system's heat can be effectively managed and dissipated.

In line with the research content of the second law of thermodynamics, the design of the evaporator and condenser models in the EV thermal management system needs to minimize the system's irreversible losses and improve overall energy efficiency. The optimization design of the evaporator and condenser, including flow channel structure, heat exchange area, and material selection, must fully consider the dynamic changes in thermal load and the comprehensive performance of the system. Especially during regenerative braking, the system needs to respond quickly to maintain stable temperature conditions, preventing overheating and performance degradation. Specifically, a U-shaped flow channel plate-fin heat exchanger type was selected for the evaporator, while a microchannel parallel-tube fin heat exchanger type was chosen for the condenser. The microchannel parallel-tube fin heat exchanger type condenser has high heat exchange capacity and low flow resistance. It condenses high-temperature and high-pressure refrigerant into liquid, releasing a large amount of heat. This heat is rapidly dissipated to the external environment, helping to maintain the temperature stability of the air conditioning system and the power battery.

In the power battery thermal management circuit and the air conditioning system circuit, the optimized use of the electric compressor can significantly improve the response speed and efficiency of the thermal management system. When regenerative braking causes the power battery temperature to rise, the electric compressor rapidly increases the circulation rate of the refrigerant, transferring excess heat from the battery and dissipating it through the condenser to the environment. This process requires the electric compressor to maintain high volumetric efficiency and isentropic efficiency under different speeds and compression ratios, ensuring the system's quick response and stable operation.

Regenerative braking significantly increases the heat of the power battery, and this extra heat needs to be quickly and effectively dissipated through the refrigeration cycle system. The expansion valve needs to precisely adjust the flow rate and state of the refrigerant based on real-time temperature and pressure changes, ensuring that the refrigeration system operates efficiently to quickly reduce the power battery's temperature and maintain its normal operating environment. Additionally, the expansion valve also plays an important role in the air conditioning system circuit. By adjusting the refrigerant flow rate, the expansion valve can effectively control the temperature of the passenger cabin, enhancing passenger comfort. In the thermal management system of EVs, the expansion valve needs to cope not only with regular thermal load changes but also with the sudden heat from regenerative braking.

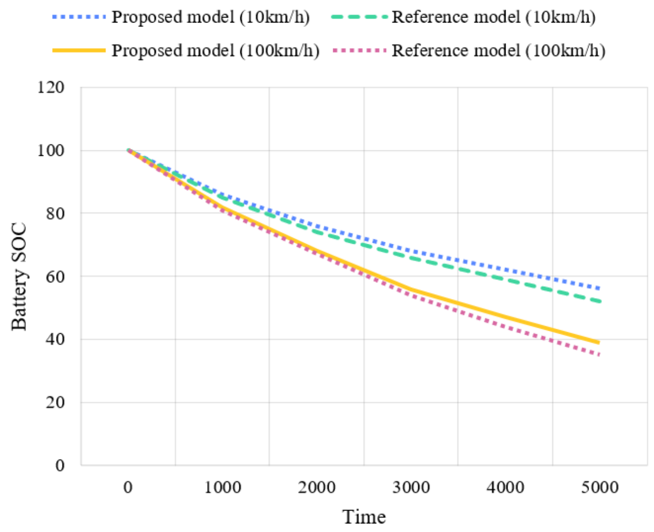
During regenerative braking, EVs generate a large amount of heat, which not only affects the temperature of the power battery but may also increase the heat inside the passenger cabin. To address this situation, the air conditioning system model needs to have a quick response capability and efficient heat exchange performance. Specifically, the air conditioning system obtains vehicle speed information through interface 1 to calculate external convective heat exchange, which helps to accurately assess the impact of the external environment on the passenger cabin temperature. Additionally, through interfaces 2 and 3, the air conditioning system can monitor and adjust variables such as the pressure, temperature, and humidity of the air entering and exiting the passenger cabin in real-time. Assuming the thermal load of the passenger cabin is represented by W_Z, the average specific heat capacity of the substance in the passenger cabin by Z_o, the equivalent concentrated mass of the passenger cabin by L, and the average temperature of the passenger cabin by S_Z, the average temperature of the passenger cabin can be calculated by the following formula:

$$W_Z(s) = Z_o L f S_Z(s) / fs \tag{14}$$

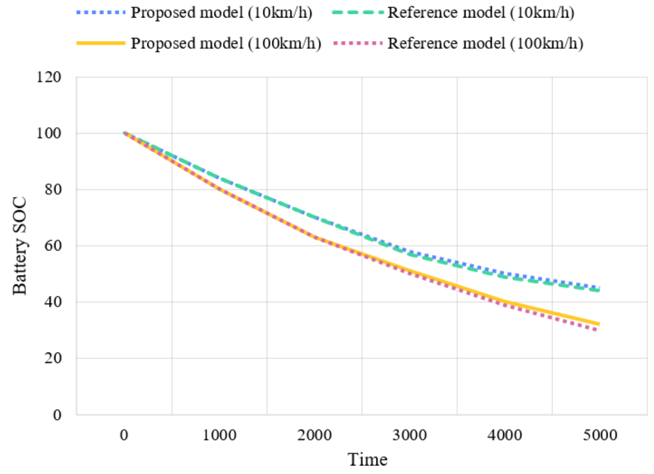
In practical applications, when regenerative braking causes a sudden increase in the system's thermal load, the air conditioning system should quickly adjust the flow rate and direction of the refrigerant to ensure that the passenger cabin temperature remains within a comfortable range. At the same time, the air conditioning system must also cooperate with the power battery thermal management circuit, reasonably distributing the cooling capacity to prioritize cooling the power battery to maintain its efficiency and safety.

4. EXPERIMENTAL RESULTS AND ANALYSIS

From the data in Figure 5, at temperatures of 0°C and -10°C, the State of Charge (SOC) of the power battery of the EV under different speeds and times shows a certain advantage of this model compared to the reference model. At 0°C, at a speed of 10 km/h, the SOC decline rate of this model is slightly lower than that of the reference model, with SOC of 56% and 52%, respectively, at 5000 seconds; at a speed of 100 km/h, the SOC retention rate of this model is more evident, with SOC of 39% and 35%, respectively, at 5000 seconds. At -10°C, at a speed of 10 km/h, the SOC decline trend of this model is similar to that of the reference model, with SOC of 45% and 44%, respectively, at 5000 seconds; however, at a speed of 100 km/h, the SOC decline rate of this model is significantly lower than that of the reference model, with SOC of 32% and 30%, respectively, at 5000 seconds. The above data analysis shows that the EV braking energy management strategy based on the second law of thermodynamics can indeed effectively optimize battery energy usage efficiency, especially at high speeds and in low-temperature environments. The SOC retention rate of this model at a high speed of 100 km/h is significantly better than that of the traditional reference model, indicating that this model optimizes the energy conversion process through the second law of thermodynamics, reduces irreversible losses, and improves energy recovery efficiency. Meanwhile, in a low-temperature environment of -10°C, the SOC of this model shows a more stable decline trend during long-term operation, further verifying that the optimized thermal management system can operate efficiently under different working conditions, ensuring the battery's driving range and service life.

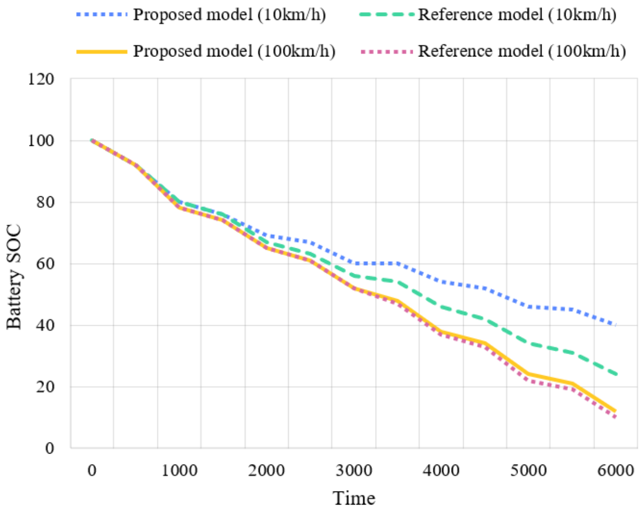


1) 0°C

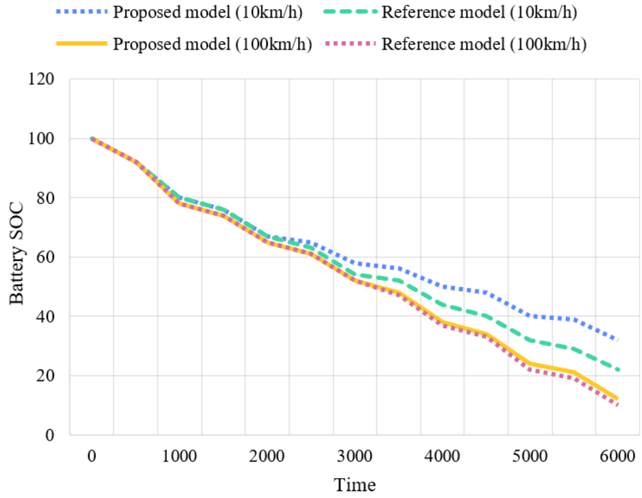


2) -10°C

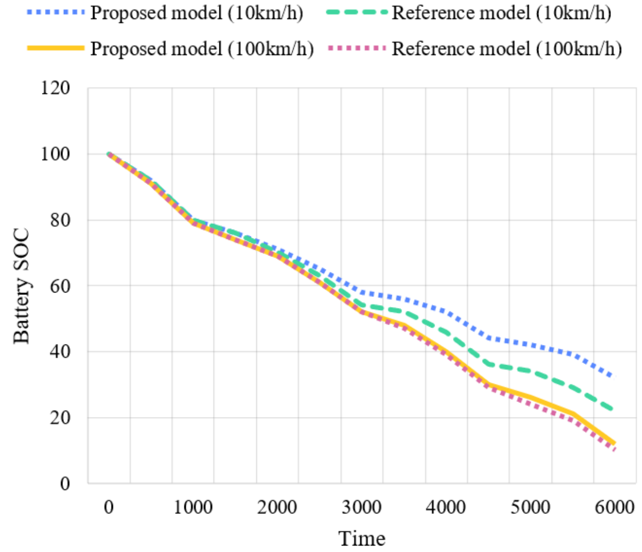
Figure 5. Simulation results of the SOC of the power battery of EVs at different temperatures



1) Driving condition



2) Auxiliary condition



3) Standby condition

Figure 6. Simulation results of the SOC of the power battery of EVs under different conditions

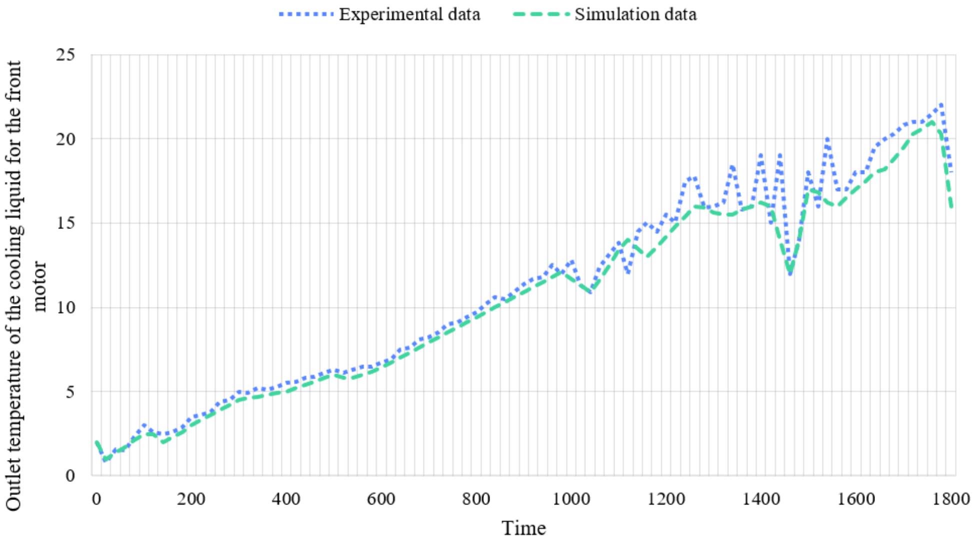


Figure 7. Outlet temperature of cooling liquid for front motor of drive system

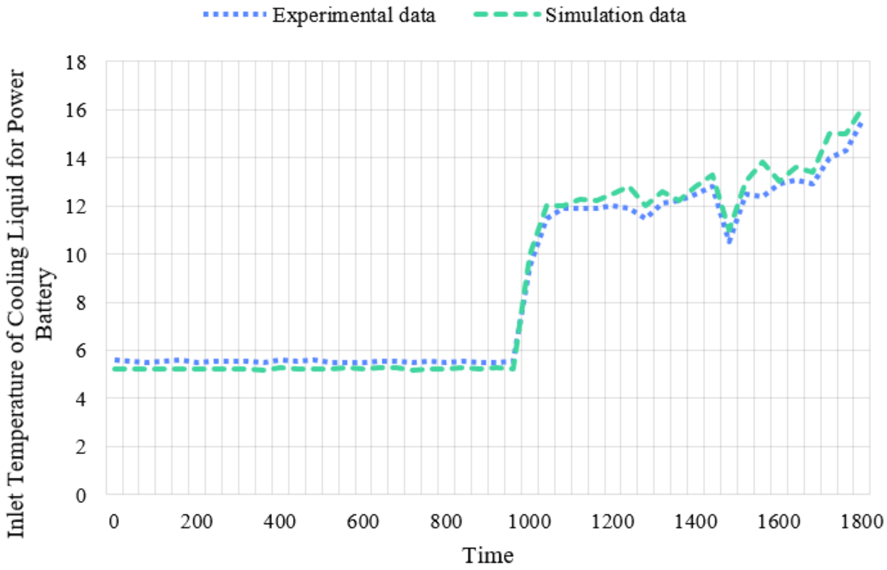


Figure 8. Inlet temperature of cooling liquid for power battery

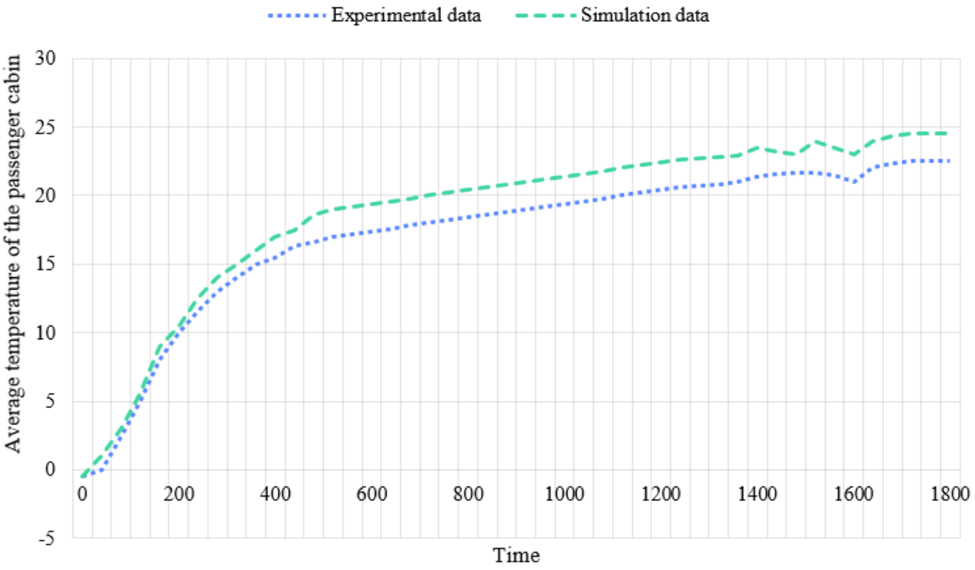


Figure 9. Average temperature of passenger cabin

From the data in Figure 6, under driving, auxiliary, and standby conditions, the SOC of the power battery of EVs over time at different speeds shows better performance in this model compared to the reference model. Under driving conditions, at a speed of 10 km/h, the SOC of this model is 40% at 6000 seconds, while that of the reference model is 24%; at a speed of 100 km/h, the SOC of this model is 12% at 6000 seconds, while that of the reference model is 10%. Under auxiliary conditions, at a speed of 10 km/h, the SOC of this model is 32% at 6000 seconds, while that of the reference model is 22%; at a speed of 100 km/h, the SOC of this model is 12% at 6000 seconds, while that of the reference model is 10%. Under standby conditions, at a speed of 10 km/h, the SOC of this model is 32% at 6000 seconds, while that of the reference model is 22%; at a speed of 100 km/h, the SOC of this model is 12% at 6000 seconds, while that of the reference model is 10%. The above data analysis shows that whether under driving, auxiliary, or standby conditions, this model can significantly reduce the SOC decline rate of the battery. This indicates that this model successfully improves battery energy utilization efficiency by deeply analyzing irreversible losses in energy conversion and optimizing the energy feedback process. Furthermore, the SOC retention rate of this model at a high speed of 100 km/h is significantly better than that of the traditional reference model, especially after long-term operation of 6000 seconds, demonstrating that the optimized thermal management system can operate efficiently under different conditions and speeds.

From the comparison between experimental data and simulation data, the outlet temperature of the cooling liquid for the front motor of the drive system fluctuates during the entire test process, but the overall trend still indicates the effectiveness of this model (Figure 7). Between 0 and 1800 seconds, the changes in experimental values and simulation values are similar at most time points; for example, at 600 seconds, the experimental value is 3.6°C, while the simulation value is 3.3°C, showing a small difference. As time progresses, the gap between experimental values and simulation values increases slightly; for example, at 1200 seconds, the experimental value is 12.5°C, while the simulation value is 11.8°C. However, overall, the trends of the two sets of data remain consistent, especially at critical temperature change nodes, indicating that the simulation model can well reflect the actual situation. Additionally, at peak temperature stages such as 1800 seconds, the experimental value is 21°C, while the simulation value is 20.3°C, and the temperature trends and changes are basically consistent, further demonstrating the accuracy and effectiveness of this model in practical applications.

From the data analysis of the inlet temperature of the cooling liquid for the power battery, the trends of the experimental values and simulation values are similar at most time points, verifying the effectiveness of the simulation model (Figure 8). Specifically, between 0 and 1200 seconds, the temperature fluctuation range of the experimental values and simulation values is small, and the gap between them is within an acceptable range. For example, at 600 seconds, the experimental value is 5.53°C, while the simulation value is 5.25°C, with a difference of only 0.28°C, showing high consistency. As time progresses, larger changes occur between the experimental values and simulation values after 1200 seconds, with the experimental value reaching 15.5°C at 1800 seconds and the simulation value being 16°C. Although there is a certain difference in absolute temperature values, the overall trends and ranges of change are basically consistent. Especially during the rapid temperature rise phase, the synchronization of experimental values and simulation values further verifies the reliability and accuracy of this model under actual working conditions.

From the data analysis of the average temperature of the passenger cabin, the experimental values and simulation values maintain a high degree of consistency at most time points, verifying the effectiveness of the simulation model (Figure 9). In the initial stage from 0 to 1000 seconds, the temperature change trends of the experimental values and simulation values are basically consistent. For example, at 800 seconds, the experimental value is 8°C, while the simulation value is 9°C, with a difference of only 1°C. In the subsequent period from 1000 to 1800 seconds, the temperature of the experimental values and simulation values continues to maintain high consistency. For example, at 1800 seconds, the experimental value is 22.5°C, while the simulation value is 24.5°C. Although there is a difference of 2°C, the overall trends and growth ranges are basically consistent. This indicates that the simulation model has good accuracy and reliability in predicting the temperature of the passenger cabin. Additionally, the simulation values are slightly higher than the experimental values at certain time points; for instance, at 1400 seconds, the simulation value is 23.5°C, while the experimental value is 21°C. These differences may be due to changes in environmental variables under actual working conditions.

Table 1. Energy consumption proportion of various parts of the vehicle under different conditions

	Normal Temperature Driving Energy Consumption	**Normal Temperature Standby Energy Consumption**	**Low Temperature Driving Energy Consumption**	**High Temperature Standby Energy Consumption**
Drive System (Front Motor)	11.26%	5.06%	3.25%	4.65%
Drive System (Rear Motor)	3.08%	5.24%	2.89%	8.36%
Air Conditioning	0	0	21.2%	0
Compressor	0	0	0	16.21%
Electronic Water Pump	0	0	0	1.65%
Radiator	0.27%	1.54%	0.13%	0.25%
Electrical Accessories	2.23%	1.67%	1.88%	2.32%
Recovered Energy	18.26%	17.3%	8%	14.2%

Table 2. Component efficiency under different conditions and temperatures

Component	Mode	Driving Energy Consumption	23°C Standby Energy Consumption	-7°C Standby Energy Consumption	35°C Standby Energy Consumption
Front Motor	Drive	85.6%	92.3%	90.6%	95%
Assembly Drive	Drive	85.8%	81.2%	79.6%	81.3%
Rear Motor Assembly	Drive	76.2%	81%	81.3%	82.6%
Electrical Accessories	-	92%	92.3%	93.6%	93.5%

From the data in Table 1, the energy consumption proportion of various parts of the vehicle under different operating conditions varies significantly. Under normal temperature conditions, the energy consumption proportion of the drive system is relatively high, with the front motor and rear motor accounting for 11.26% and 3.08%, respectively. In the normal temperature standby state, the energy consumption proportion of the drive system decreases, with the front motor at 5.06% and the rear motor at 5.24%. Under low temperature driving conditions, the energy consumption proportion of the air conditioning system rises sharply to 21.2%, due to the increased demand for interior heating in a low-temperature environment. In the high temperature standby state, the energy consumption proportion of the compressor reaches 16.21%, with the electronic water pump and radiator at 1.65% and 0.25%, respectively, indicating increased cooling demand in a high-temperature environment. Recovered energy occupies a certain proportion under various conditions, being 18.26% and 17.3% in normal temperature and standby states, and 8% and 14.2% in low and high-temperature states, respectively, showing that the efficiency of the energy recovery system varies with different ambient temperatures. The data indicate that under low and high-temperature conditions, the energy consumption of the air conditioning system and compressor increases significantly. However, by optimizing the energy feedback process, it is possible to alleviate the impact of high-energy-consuming components on overall vehicle performance to a certain extent. For example, under low temperature driving conditions, although the air conditioning energy consumption proportion reaches 21.2%, the effective energy recovery proportion of 8% improves overall energy efficiency. Similarly, under high temperature standby conditions, despite the compressor energy consumption proportion being 16.21%, the recovered energy proportion is 14.2%, proving the importance of the energy recovery system in high-temperature environments.

From the data in Table 2, the efficiency of various components of the EV varies significantly under different conditions and temperatures. In drive mode, the efficiency of the front motor assembly is 85.6% at a normal temperature of 23°C, while in standby mode, this efficiency increases to 92.3%. Under low temperature (-7°C) and high temperature (35°C) conditions, the standby efficiency of the front motor assembly is 90.6% and 95%, respectively, indicating that temperature changes have a certain impact on the standby efficiency of the front motor assembly. Similarly, the efficiency of the rear motor assembly in drive mode is 76.2% at normal temperature, while the standby efficiency at normal temperature is 81%, and it is 81.3% and 82.6% under low and high temperature conditions, respectively. In addition, the efficiency of electrical accessories varies little under different temperature conditions, remaining above 92%, showing their stable working characteristics.

By analyzing the efficiency data of the above components, it can be concluded that the EV braking energy management strategy based on the second law of thermodynamics can effectively improve the efficiency of components under different conditions and temperatures. The data show that in drive mode, the efficiency of the front and rear motors is relatively stable under different temperature conditions, with the front motor reaching a maximum efficiency of 95% under high temperature standby conditions, and the rear motor reaching 82.6% under high temperature standby conditions. This high-efficiency operation indicates that by optimizing the energy feedback process, the system can maintain efficient operation under different temperature conditions, reducing irreversible losses in energy conversion. Furthermore, the efficiency of electrical accessories fluctuates little under different temperature conditions, demonstrating strong stability, further verifying the effectiveness of the energy management strategy.

In summary, through in-depth analysis and optimization of the regenerative braking process, this paper successfully improves the efficiency of various components of EVs under different temperatures and conditions, proving the significant advantages and practicality of the energy management strategy based on the second law of thermodynamics in practical applications.

5. CONCLUSION

Through research in two main parts, this paper deeply explores the regenerative braking process of EVs based on the second law of thermodynamics and its optimization path. On this basis, a vehicle thermal management system model was established, with parameter settings and optimization conducted. Experimental results show significant differences in the efficiency of various components of EVs under different temperatures and conditions. Specifically, the front motor assembly achieves the highest efficiency of 95% under high-temperature standby conditions; the rear motor assembly reaches an efficiency of 82.6% under high-temperature standby conditions; and the efficiency of electrical accessories remains above 92% under all temperature conditions, showing high stability. Additionally, the simulation results of the power battery SOC indicate that different temperature and operating conditions have a significant impact on the state of the battery. The optimization of parameters such as the outlet temperature of the cooling liquid for the front motor of the drive system, the inlet temperature of the cooling liquid for the power battery, and the average temperature of the passenger cabin effectively improves the energy utilization efficiency of the entire vehicle.

The research in this paper fills the gap in existing studies on the regenerative braking process and vehicle thermal management system optimization of EVs. By revealing the irreversible losses in energy conversion and proposing optimization paths, this study not only improves the system's efficiency under different temperatures and conditions but also proves the significant advantages of the energy management strategy based on the second law of thermodynamics in practical applications. Particularly, through the in-depth analysis of the regenerative braking process, we can better understand and optimize the energy conversion and management process of EVs, thereby improving overall efficiency and performance.

Although this paper has made significant progress in the energy management of EVs, some limitations still exist. Firstly, the experimental data are mainly based on simulation results, and the complexity and variability of actual operation may lead to deviations from expected results. Secondly, this study mainly focuses on efficiency optimization under different temperatures and conditions, while other influencing factors such as long-term operation and different driving habits have not been thoroughly explored. Future research should further verify and refine the simulation results, optimize energy management strategies through real vehicle tests and long-term data accumulation. Additionally, combining artificial intelligence and big data technologies, more intelligent and adaptive thermal management systems should be developed to further enhance the overall energy efficiency and user experience of EVs.

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