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Performance Research on Heating Performance of Battery Thermal Management Coupled with the Vapor Injection Heat Pump Air Conditioning

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Abstract: Compared to the use of positive temperature coefficient (PTC) materials that consume electrical energy for low-temperature heating, heat pump air conditioners can provide more energy-efficient heating performance by absorbing and utilizing heat from the outdoor air to heat the cab in order to improve the range of electric vehicles. In addition, in order to make the battery work under safe working conditions, this paper proposes battery thermal management coupled with vapor injection heat pump air conditioning. The system is modeled and analyzed through simulation, and the impact of the compressor speed and ambient temperature changes in the battery cooling performance of the system. The results show that under different compressor RPM (Revolution Per Minute) with an ambient temperature of 5 °C, the average temperature of the battery pack remains below 30 °C, and the majority of individual cell temperatures are maintained within the range of 20 to 35 °C. At a constant compressor RPM of 4000/min under varying ambient temperatures, the average temperature of the battery pack remains below 30 °C, with the majority of individual cell temperatures staying within the range of 20 to 35 °C. And the battery cooling performance still performs well. In the low temperature of −10 °C and −20 °C, the system can still maintain a relatively stable heating capacity compared with the 2009.1W, provided by the environment temperature of 5 °C at the same RPM.

Keywords: KULI; battery thermal management; vapor injection; heat pump; economizer; modeling and simulation

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1. Introduction

When it comes to electric vehicles, the central component is unequivocally the battery. The battery provides energy to the vehicle's air-conditioning system and realizes the functions of cooling, heating and defrosting [1]. When the power battery works, the chemical energy is converted into electrical energy and internal energy, and if the internal energy is not released in time, the battery will be in a non-optimal state for a long time, accelerating the aging process, and even leading to a battery explosion, which is dangerous to the lives of the vehicle's occupants. Consequently, establishing effective thermal management for electric vehicles becomes of paramount importance for ensuring they are secure and in optimal operation.

Moreover, the range of electric vehicles and their heating functionality experience significant challenges in low temperatures, demanding urgent resolution. The establishment of test platforms and vehicles, taking into thorough consideration environmental factors and other variables, entails a protracted lead time and substantial costs. This, in turn, amplifies the research and development (R&D) expenses associated with creating novel models. Nevertheless, leveraging simulation modeling holds the promise of ameliorating these challenges significantly. The strategic integration of simulation and experimentation not only enhances the precision of simulation outcomes, but it also simulates conditions that are arduous to simulate in actual operational environments. This approach serves to curtail the need for extensive experimentation, thereby mitigating R&D costs.

The advocacy for electric vehicles is an inevitable trend in the transformation of human society's transportation from oil-based vehicles to electric alternatives. This paradigm shift can also improve the efficiency of energy utilization, and at the same time, electric vehicles can greatly reduce the emission of pollutants, which is conducive to promoting human society to complete the transformation to the social pattern of "green energy". Moreover, the technical advancement of electric vehicles has been emphasized by many countries and enjoys policy support. A multitude of academic experts are investigating various facets of electric vehicles, including but not limited to the power system, air-conditioning system, braking system, and automated driving system.

Zhang et al. [2] proposed an external battery heating system with an electric heating film applied to the battery and developed a fuzzy logic control strategy, which optimizes the external heating power so that the car can receive a greater range before the end of the battery pack discharge. Dong et al. [3] tested the cooling and heating performance of R134a and R744 refrigerants in different heat pump configurations. The results showed that the cooling and heating performance of the R744 system was comparable to that of the R134a system, and the R744 system was able to maintain a high heating COP in the temperature range from −20 °C to −25 °C. Han et al. [4] studied the air-conditioning system with an air-injection heat pump using waste heat recovery technology, and found that compared with the single air-supplementing system, the heat-pump system using 2 kW waste heat can increase the heating capacity and the COP by 1.61% and 1.38%, respectively. Liso et al. [5] built a control-oriented dynamic model of liquid-cooled proton exchange membrane fuel cell system and investigated the change in a working temperature during the rapidly changing load. Li et al. [6] carried out an innovative framework of the electric drive cooling circuit through KULI and put forward the corresponding control strategy. In total, three simulation results showed that this method not only improved the efficiency of pump, but also played a good role in temperature control. Tian et al. [7] put forward an electric vehicles thermal management system (EVTMS), focusing on the effects of waste heat and condensation temperature on the performance of the EVTMS. The results showed that increasing the waste heat and reducing the condensation temperature are conducive to the performance optimization of EVTMS. Dilbaz et al. [8] investigated and analyzed the thermal performance of 20 Ah rectangular battery packs cooled by water and nanodiamond-Fe_3O_4 water/ethylene glycol (ND- Fe_3O_4 W/EG) hybrid nanofluid. The results show that increasing the Reynolds number and nanoparticle volume ratio improves the temperature distribution and reduces the maximum temperature in the battery pack. The maximum temperature of the ND- Fe_3O_4 + W/EG hybrid nanofluid (2% volume ratio, 800 Re) was increased by 23.1% compared to water with the same Reynolds number. Jose et al. [9] explored research methodologies to enhance air conditioning efficiency and reduce energy consumption. They introduced a solution for zonal air conditioning of occupant spaces, demonstrating a remarkable 51% reduction of energy consumption compared to full-space air-conditioning approach. Xu et al. [10] established an experimental platform for a low-temperature refrigerant injected heat pump system and proposed the applicable temperature under different control strategies. Additionally, the heating performance of the system was compared without the use of these strategies. Wei et al. [11] proposed a novel vapor injection heat pump cycle with indirect heat recovery. Under similar operating conditions, the volumetric heating capacity of this cycle is shown to improve by 33% to 72% compared to the conventional sub-cooler vapor injection heat pump cycle. Additionally, the coefficient of performance is enhanced by 20.5% to 33.5%. The newly proposed cycle is deemed suitable for utilization in lower ambient temperatures. A battery thermal management system can not only reduce the waste heat loss of the system or equipment and improve energy utilization, but can also assist the battery to be maintained in the optimal operating temperature range; if the battery is often in the poor operating temperature, the battery overheating is likely to lead to the impact of the battery discharge multiplier, power density and the total capacity, and accelerate the aging of the battery and the occurrence of thermal runaway phenomenon, leading to the risk of combustion and explosion. Overcooling of the battery will reduce the battery activity and lead to poor performance in winter [12].

To summarize, in order to maintain the battery in a good working condition as well as maintain the heat pump system to keep high thermal performance in a low-temperature environment, this paper proposes battery thermal management coupled with vapor injection heat pump air conditioning as the focus of research. The first part of this article is to model the battery thermal management coupled with vapor injection heat pump air conditioning system using KULI 16.1, including setting the parameters of its components, the second part is the selection of refrigerant varieties, and the third part is to analyze the effect of compressor speed change and ambient temperature change in the system's heating performance and battery cooling performance using the single-variable method in the KULI lab software.

2. Materials and Methods

2.1. Establishment of Simulation Model of Battery Thermal Management Coupled with Vapor Injection Heat Pump Air Conditioning (AC)

KULI achieves vehicle thermal management simulation through parameter settings among components and between components and the system [13]. It employs semi-empirical formulas to construct models based on the principles of thermodynamics and heat transfer, followed by simulations based on user data. The software is divided into five modules based on functionality: the HVAC module is applied for simulating air conditioning systems; the base module includes components such as radiators and fans for cooling systems; the advanced module is employed for collaborative simulations with other software; the drive module is used to simulate transient vehicle conditions; and the component module assists users in constructing additional elements [14]. Through the simulation with KULI16.1 software, the complete model includes the cooling and heating loop of heat pump air-conditioning and the cooling and preheating loop of the battery pack. The working principle of the system is shown in Figure 1:

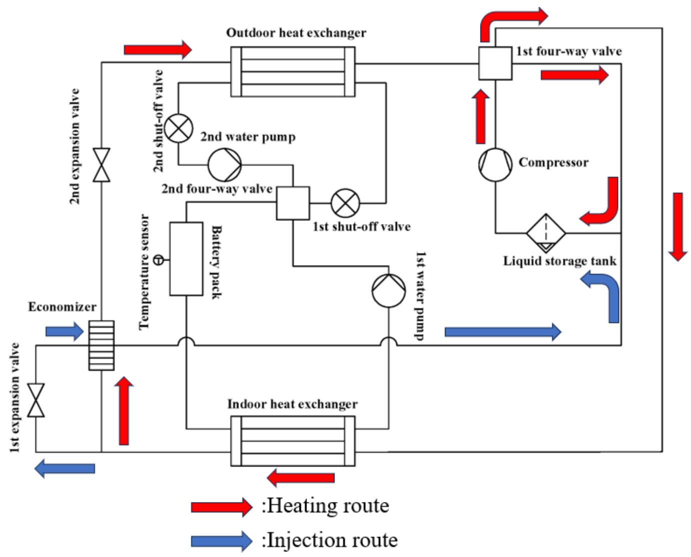

Figure 1. Battery thermal management coupled with vapor injection heat pump AC.

Different from the traditional single-stage compression heat pump air-conditioning, vapor injection heat pump air-conditioning increases the refrigerant flow through the whole system by adding an auxiliary pipe line, When the refrigerant passes through the indoor heat exchanger, the refrigerant splits into two, one way flows to the economizer, and another way flows to the 1st expansion valve, which is called the injection route, after passing through the economizer. After the high temperature refrigerant is exchanged with the low-temperature refrigerant at the economizer, the refrigerant flowing to the outdoor heat exchanger gains subcooling, the refrigerant flowing to the storage tank gains superheat, and the refrigerant gaining superheat meets with the refrigerant in the heating route, ultimately flowing to the storage tank and the compressor. The addition of the auxiliary pipeline produces further subcooling and improves the system's ability to absorb more heat at low-temperatures, and the injected vapor prevents the refrigerant flow back to the compressor from being insufficient due to the low ambient temperature, and thus, weaken the heat capacity of the compression mechanism. In addition, in the low-temperature environment, the outdoor heat exchanger is susceptible to frosting, leading to a diminished heat exchange capacity. To address this issue, the cooling water within the pipeline undergoes an initial heat exchange process with both the battery and the indoor heat exchanger via the secondary water pump within the battery circuit. Subsequently, this pre-conditioned coolant is directed to the outdoor heat exchanger via the primary water pump, facilitating heat exchange and defrosting. This battery circuit serves a dual purpose by preventing excessive heat emanating from the battery that may disrupt normal operations, while concurrently enhancing the heat exchange capability of the outdoor heat exchanger in low-temperature environments.

When KULI 16.1 software is used for simulation analysis, the heat pump air conditioning system can be abstractly regarded as the integration of the air-conditioning circuit and the battery thermal management circuit; then, there are several assumptions about the physical phenomena between the system and each component [15]:

1. The operational characteristics of the compressor are collectively determined by the compression ratio, compressor speed, and compressor displacement;
2. Refrigerant flows adiabatically in the expansion valve;
3. Refrigerant only flows in one dimension inside the outdoor heat exchanger and indoor heat exchanger, ignoring the influence of gravity and axial change;
4. Ignore the wall thermal resistance of outdoor heat exchanger and indoor heat exchanger;
5. Ignore the leakage of refrigerant in the circulation circuit.

Establishing the battery thermal management coupled with a vapor injection heat pump AC in the low-temperature environment with KULI 16.1, as illustrated in Figure 1, simplifies the model for building the air-conditioning circuit as well as the battery thermal management circuit, in accordance with the working principal diagram in Figure 2:

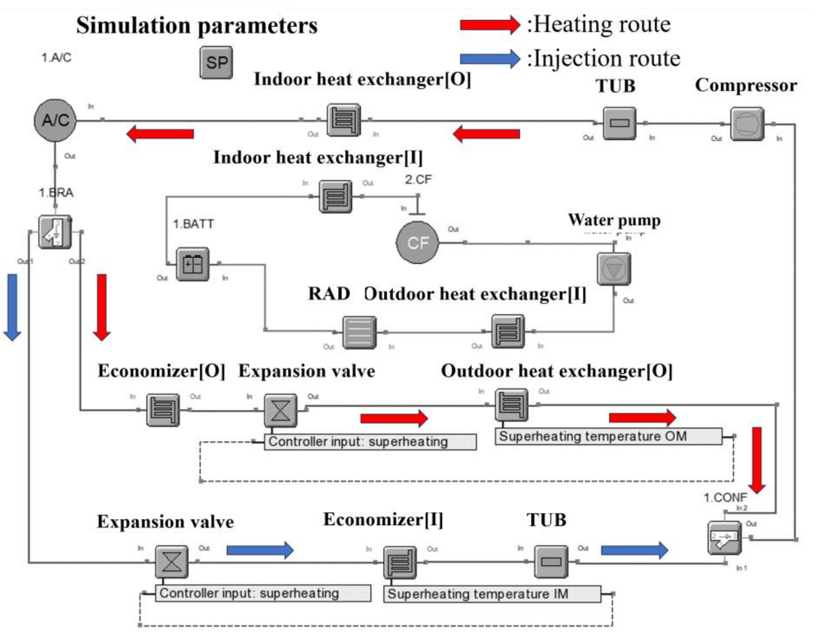

Figure 2. The vapor injection heat pump air-conditioning system model.

In the case of cooling or heating, the coefficient of performance (COP) is a metric used to measure the performance of energy conversion devices such as heat pumps, refrigeration units, and air-conditioning systems. COP stands as a pivotal metric in the evaluation of heat pump air-conditioning systems, representing the ratio of the refrigerating capacity (or heating capacity) to the power consumption of the compressor during the cooling (or heating) mode. It holds significance as a key parameter for system measurement. In the realm of heat pump air-conditioning, the refrigerant, in principle, undergoes four fundamental processes: isentropic compression, isobaric condensation, adiabatic expansion, and isobaric evaporation [16].

$$COP = \frac{Q_h}{P} \tag{1}$$

In the above equation: Q_h refers to the refrigerating (heating) capacity, W; P refers to the compressor power consumption, W.

2.1.1. Establishment of Compressor Module

According to the ratio of the compressor speed to pressure, input volumetric efficiency and isentropic efficiency data into KULI 16.1 to build a compressor model. The calculation formulas of volumetric efficiency and isentropic efficiency obtained by the relevant literatures are as follows [17,18],

$$\text{Volumetric efficiency } \eta_v\text{: } \eta_v = \frac{q_m}{\rho_{suc} \cdot N \cdot disp} \tag{2}$$

In the above equation: q_m refers to the mass flow rate, kg/s; ρ_{suc} refers to suction density, kg/m^3; $disp$ refers to compressor displacement, m^3; N refers to the rotary speed of the compressor, rev/s.

$$\text{Isentropic efficiency } \eta_{is} : \ \eta_{is} = \frac{h_{dis} - h_s}{h_d - h_s} \tag{3}$$

In the above equation: h_{dis} refers to isentropic discharge specific enthalpy, J/kg; h_s refers to suction specific enthalpy, J/kg; h_d refers to discharge specific enthalpy.

2.1.2. Establishment of Battery Pack

The battery pack module uses KULI's own module, and the module parameter and the battery pack structure are set as shown in the following Figure 3 and Table 1. Flow way is established using liquid through the battery.

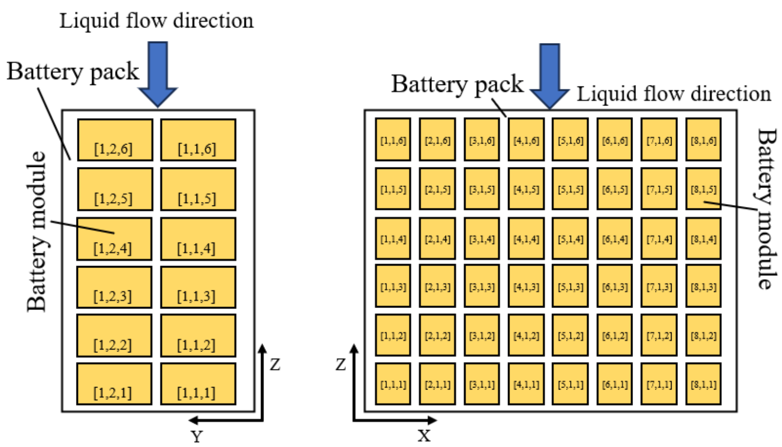

Figure 3. Two-dimensional diagram of a three-dimensional structure of battery pack.

Table 1. Battery module parameter settings.

Parameter	Specific Numerical
Battery module capacity module [Ah]	14.5
Initial temperature [°C]	25
Initial SOC [%]	99
Operating point Target current [A]	150
Geometry	Cuboid
Modules in x-direction	8
Modules in y-direction	2
Modules in z-direction	6

2.2. Refrigerant

The refrigerant plays a crucial role as a component within the entire air-conditioning system, facilitating heat exchange with the external environment and the transfer of heat. Different refrigerants exhibit varying cooling capacities, thereby influencing the cooling and heating capabilities of the air-conditioning system. R134a commonly serves as the refrigerant in electric vehicle heat pump air-conditioning systems. Despite R134a's zero ozone depletion potential (ODP), its global warming potential (GWP) is alarmingly high, reaching 1300. In response, the European Union implemented pertinent legislation in 2006, mandating the phase-out of R134a for new research and development vehicles by 2011, followed by its prohibition in new production vehicles by 2017 [19]. This paper focuses on investigating R1234yf as the subject of study—an environmentally friendly refrigerant. Notably, R1234yf boasts a zero ozone depletion potential (ODP) and exhibits an exceptionally low global warming potential (GWP). Utilizing R1234yf as the operational medium in the air conditioning circuit signifies a more environmentally conscious and a cleaner approach. Conversely, CO_2, considered a more environmentally friendly refrigerant, suffers from higher system pressure and reduced energy efficiency due to its critical pressure of 7.4 MPa and critical temperature of 31.1 °C. Consequently, R1234yf demonstrates greater potential for development. The ensuing Table 2 delineates the fundamental characteristics of refrigerants R1234yf, R134a, CO_2, and R290 [20].

Table 2. Basic characteristics of refrigerants [20].

Characteristics	R1234yf	R134a	CO_2	R290
Boiling point/°C	−29.4	−26.1	−78.5	−42.2
Critical temperature/°C	94.7	101.1	31.1	96.7
Critical pressure/MPa	3.4	4.1	7.4	4.2
Security level	A2L	A1	A1	A3
ODP	0	0	0	0
GWP	4	1300	1	3

3. Results

3.1. Impact of Different Speeds of Compressor RPM

In order to study the influence of compressor speed on the cooling of the battery, the steady-state simulation was carried out in the laboratory of KULI16.1. The simulation parameters are shown in Table 3:

Table 3. First time steady-state simulation parameters.

Operating Point	1	2	3	4	5
RPM Compressor [1/min]	2000	3000	4000	5000	6000
Driving speed [km/h]	60	60	60	60	60
Ambient pressure [kPa]	101.3	101.3	101.3	101.3	101.3
Ambient temperature [°C]	5	5	5	5	5
Ambient humidity [%]	20	20	20	20	20
A/C on	On	On	On	On	On

According to the above parameter values, relevant data of entry and exit water temperatures and average temperatures of cells in the following battery circuits are obtained, as shown in Figure 4:

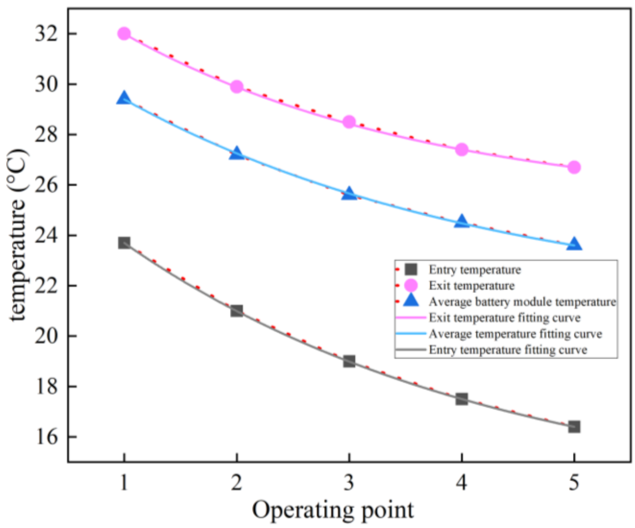

Figure 4. Entry and exit water temperature and average battery module temperature.

In addition, the battery temperature distribution diagrams of RPM 2000, 3000, 4000, 5000, and 6000/min are shown in Figure 5:

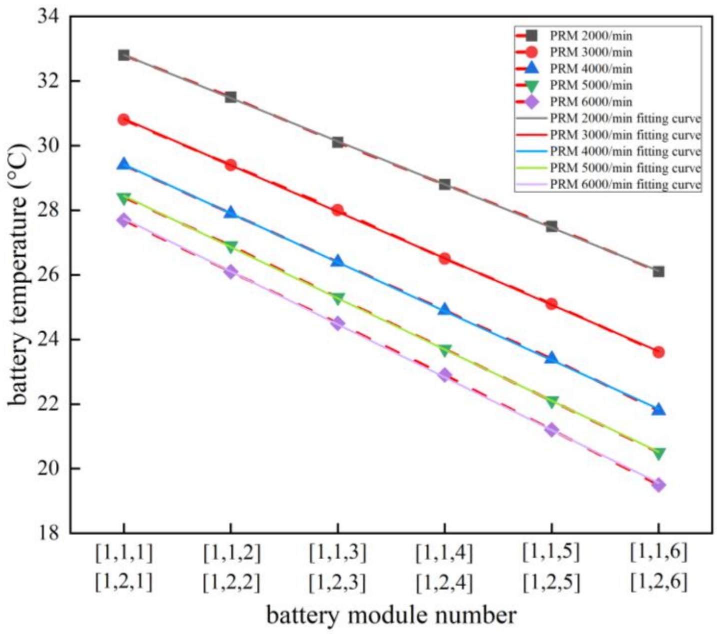

Figure 5. Battery temperature distribution diagram.

As illustrated in Figure 4, the augmentation of the compressor speed proves advantageous in mitigating both entry and exit water temperatures. Upon reaching a speed of 2000/min, the entry and exit water temperatures reach 32 °C and 23.7 °C, respectively. The average battery temperature can reach below 30 °C across all operational scenarios. In order to prevent the battery from aging faster, due to exceeding the operating temperature range, the best operating temperature is 20~35 °C [21]. Examining the battery temperature distribution diagram of Figure 5, the cooling water initiates its flow from the foremost position of the battery pack [1,1,6] and [1,2,6]. Due to the substantial temperature disparity between the inlet water and the battery pack, a good heat exchange with the front-end battery is achieved. This exchange leads to a temperature increase in the cooling water, which then sequentially traverses through [1,1,5], [1,1,4], and so forth, ultimately exiting from [1,1,1] and [1,2,1]. Moving towards the rear, the temperature of the cooling water gradually approaches that of the battery pack. Consequently, the heat exchange capacity of the cooling battery diminishes. The increase in compressor RPM amplifies the refrigerant flow rate in the outdoor heat exchanger within the low-pressure section of the air conditioning circuit. This, in turn, augments the heat exchange between the outdoor heat exchanger and the battery circuit, resulting in a decrease in the temperature of the cooling water flowing to the battery pack. However, it is noteworthy that a higher compressor RPM does not universally translate to a more effective cooling effect, as evidenced by Figure 5, wherein the temperature difference for the same battery pack number gradually diminishes across varying RPMs. This phenomenon arises from the decreasing temperature difference between the cooling water inlet and the battery thermal management circuit at a different compressor RPM.

According to the compressor performance parameters obtained in Figure 6, when the compressor RPM increases, the driving power by the compressor also increases, while the COP decreases from 2.11 to 1.58. However, the heating capacity of the indoor heat exchanger does not show an increasing relationship, but when the compressor reaches 4000/min, the heating capacity reaches the maximum value among the entire compressor RPM. To sum up, although the RPM of the compressor increases, the COP of the heating system decreases because the COP is not only related to the energy consumption of the compressor, but also to the heating capacity of the system. In practice, although the increase in the compressor is beneficial to the heat dissipation of the battery, it not only makes the heating effect worse in the low-temperature environment, but also increases the energy consumption of the compressor, which fails to meet the driver's driving requirements. When the compressor speed is set at 4000/min, as indicated by Figures 4 and 5, the average temperature of the battery module is found to be 25.6 °C. The maximum temperature of the battery module does not exceed 35 °C, and the minimum temperature remains above 20 °C. This effectively maintains the battery within an optimal operational temperature range, with a relatively higher heat supply at this rotational speed. Consequently, the next section will explore the impact of varying environmental temperatures as a single variable on battery cooling, maintaining the constant compressor RPM of 4000/min.

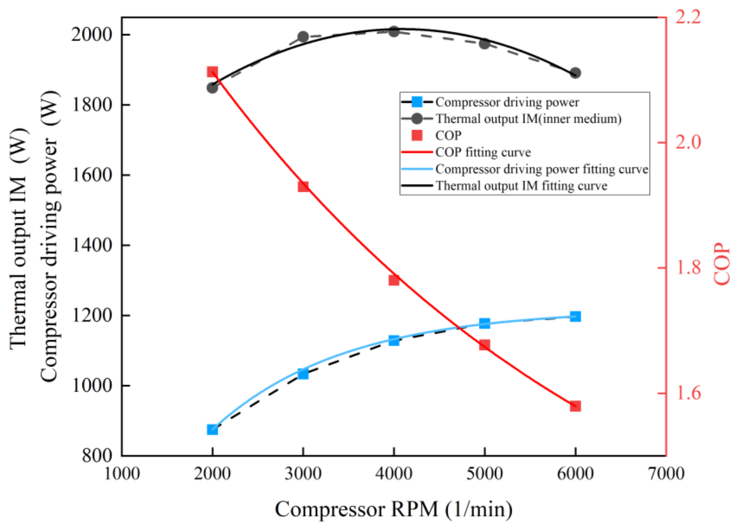

Figure 6. Ambient temperature of 5 °C as performance parameter.

3.2. Impact of Different Ambient Temperatures

In order to study the influence of ambient temperatures on the cooling of battery pack, the steady-state simulation was carried out in the laboratory of KULI 16.1. The simulation parameters are shown in Table 4:

Table 4. Second time steady-state simulation parameters.

Operating Point	1	2	3	4
RPM Compressor [1/min]	4000	4000	4000	4000
Driving speed [km/h]	60	60	60	60
Ambient pressure [hPa]	1013	1013	1013	1013
Ambient temperature [°C]	10	0	−10	−20
Ambient humidity [%]	20	20	20	20
A/C on	On	On	On	On

According to the above parameter values, relevant data of entry and exit water temperatures and average temperatures of cells in the following battery circuits are obtained, as shown in Figure 7:

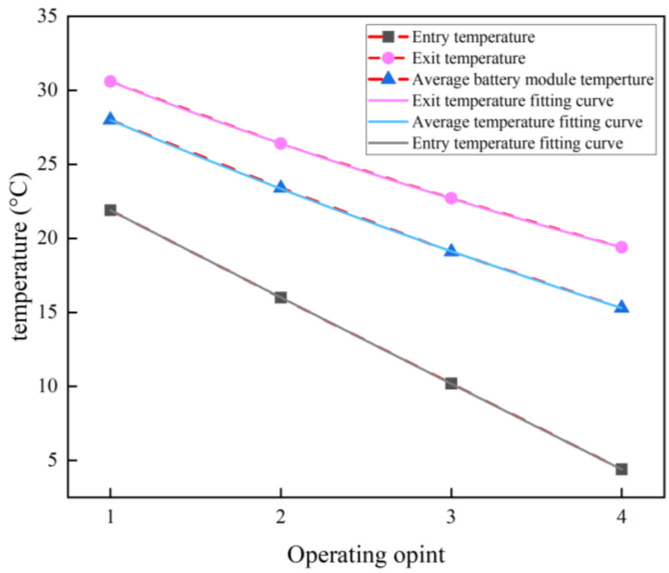

Figure 7. Entry and exit water temperature and average cell temperature.

In addition, the battery temperature distribution diagrams for ambient temperature of −20, −10, 0, and 10 °C are shown in Figure 8:

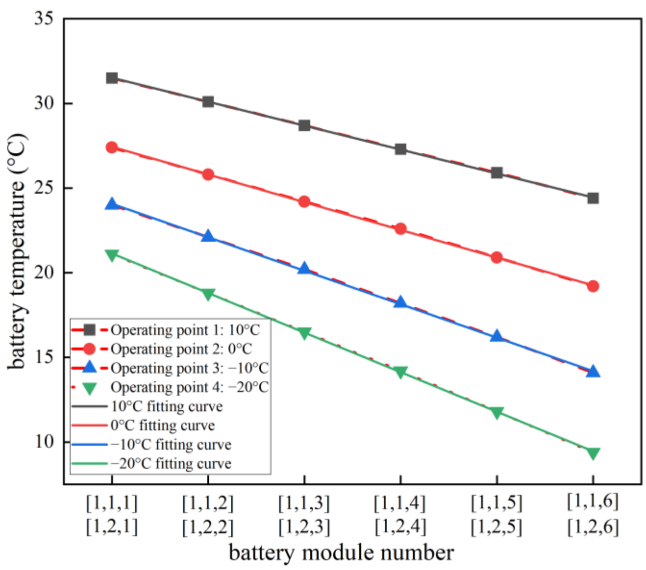

Figure 8. Battery temperature distribution diagram.

As can be seen from Figure 7, with the decrease in the ambient temperature, the entry and exit water temperatures of the battery gradually decrease, with the lowest water temperature being around 4.4 °C and the average battery module temperature being below 30 °C. It can be seen from the temperature distribution diagram of the battery in Figure 8, that the maximum temperature is about 21.1 °C and the minimum temperature can reach about 9.4 °C at an ambient temperature of −20 °C. When the ambient temperature drops, the temperature difference between the outdoor heat exchange of the battery thermal management circuit and the ambient temperature becomes larger, the heat exchange capacity is enhanced, and the temperature of the cooling water of the battery thermal management circuit drops, so the cooling water can better dissipate heat for the battery pack. From the above mentioned optimal operating temperature of the battery is 20–35 °C, the cooled battery at an ambient temperature of −20 °C is far below this temperature range and is in a state of over-cooling, which will affect the working performance of the battery pack. Therefore, when the ambient temperature is lower than −10 °C, the battery pack can be considered without cooling.

Based on the compressor performance parameters extracted from Figure 9, it is observed that a reduction in ambient temperature correlates with a proportional decrease in the power consumption of the compressor. Simultaneously, the coefficient of performance (COP) increases from 1.73 to 1.95. Meanwhile, the heating capacity of the indoor heat exchanger demonstrates a subtle inverse relationship with an ambient temperature decline. In summary, the compressor power diminishes in tandem with decreasing ambient temperature. This phenomenon is attributed to the corresponding reduction in the evaporation pressure of the outdoor heat exchanger, subsequently leading to a decrease in the inlet pressure of the compressor. Consequently, a diminished volume of refrigerant enters the compressor, resulting in lower energy consumption by the compressor. Since the COP is intricately linked to both heat and compressor energy consumption, the reduction in compressor power surpasses that of heating capacity, thereby causing a marginal increase in the COP.

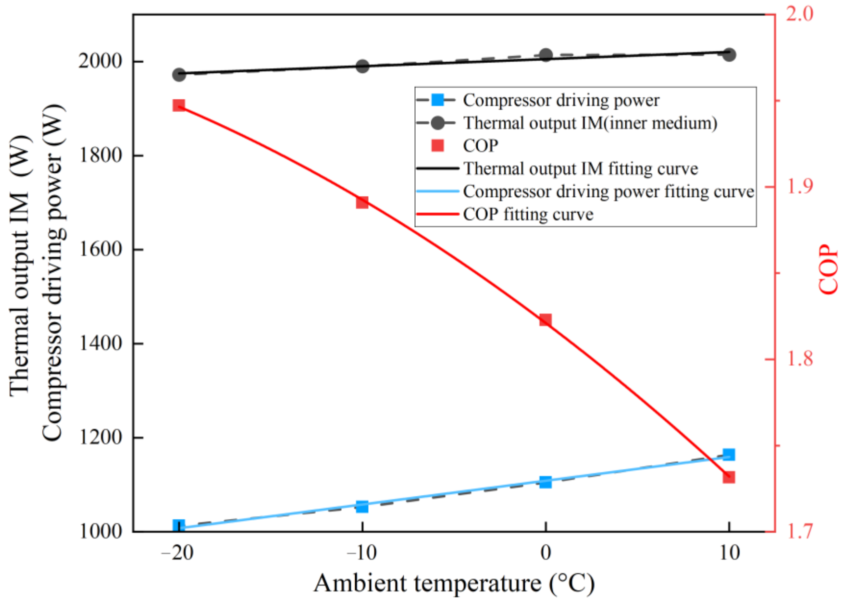

Figure 9. RPM compressor 4000/min performance parameter.

4. Conclusions

In order to realize the heating of electric vehicles in a low-temperature environment and ensure the normal operation of batteries through the technology of battery thermal management, based on the above steady-state simulation experiment of battery thermal management, coupled with vapor injection heat pump air conditioning for compressor speed and ambient temperature, the following conclusions are drawn by analyzing the simulation experiment:

(1) Based on the simulation results, at different compressor RPMs with an ambient temperature of 5 °C, the average temperature of the battery pack remains below 30 °C, and the majority of individual cell temperatures are maintained within the range of 20 to 35 °C. Additionally, under the constant compressor RPM of 4000/min, despite the occurrence of individual cell temperatures below 20 °C in the −20 °C cold environment, under conditions of 10 °C, 0 °C, and −10 °C, most individual cell temperatures still stay within the range of 20 to 35 °C. Therefore, the thermal management performance proposed in this paper is better, ensuring that the battery operates within an optimal temperature range and meets cooling requirements.
(2) In the low-temperature environment of −10 °C and −20 °C, the system can still provide 1990 W and 1971.9 W of heat respectively, and it can still maintain a relatively stable heating capacity compared with the 2009.1 W, provided by the environment temperature of 5 °C at the same RPM, which indicates that vapor injection heat pump air-conditioning still has a good heating capacity in the low-temperature environment.
(3) The limitation of this paper is that the results are still in the simulation phase of the theoretical. When the ambient temperature is lower than −20 °C, the battery thermal management circuit of the system can be considered to turn off the water pump cooling work; the temperature sensor on the battery pack is used to detect whether the battery pack continues to heat up in the later stage of the work if the detection temperature is more than 30 °C, and then consider opening the battery thermal management circuit of the water pump for cooling work. There is few research on battery management and vapor injection heat pump air-conditioning, and there may be some deviation between the simulation results and the actual situation. The results still need to be further studied and analyzed to optimize the system and verify the experiments.
(4) The performance of vapor injection heat pump air-conditioning is examined in this essay in relation to ambient temperature and compressor speed. In fact, the performance of the system is also influenced by the pump's flow rate or the expansion valve's opening, which will be researched further in the future for vapor injection heat pump air-conditioning.

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