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How electric vehicle energy flow is distributed in low-temperature conditions under real-world driving?#

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ABSTRACT

Electric vehicles are essential for decarbonizing transport, though many challenges lie ahead. One issue that has received recent attention is the gap between real-world battery energy consumption and results from laboratory tests, especially in winter, where the operational status of thermal management system (TMS), including air conditioning (AC) system, varies greatly. Despite the critical importance of TMS for safety anddriving range performance, the precise contribution of TMS to battery and cabin energy consumption remains elusive. Through a comprehensive expermental analysis of the energy flow characteristics and consumption patterns of a certain four-wheel-drive multi-purpose vehicle (MPV) under diverse low-temperature conditions (-7 °C, -20 °C), we elucidated the operational traits of the primary energy-consuming components in cold environments, with particular emphasis on the vehicle's overall energy consumption. Based on the standardized CLTC-P test procedure, our experimental findings reveal a pronounced increase in the overall energy consumption of EVs in low-temperature environments, with energy consumption recorded as 6.8 kW.h, and 8.9 kW.h, respectively. Notably, the energy consumption attributed to the battery thermal management system accounts for 54.0 %, and 59.8 %, while the propulsion system's motor drive energy consumption represents 43.8 %, and 38.0 %, respectively. Furthermore, under the two low-temperature conditions, the activation of the air conditioning system incurs an additional energy consumption of 16.60 %, and 18.44 %, respectively. Notably, the energy consumption surge is more pronounced when the air conditioning is activated, with energy consumption increasing by up to 287.65 % at -20 °C, compared with the standard working condition, corresponding to a 74.20 % decline in driving range, which further elucidating the mechanistic effects of temperature variations on the performance of the thermal management system in electric vehicles. These research findings not only contribute to a deeper understanding of the energy utilization status of electric vehicles in adverse climate conditions but also provide crucial guidance for the design of more environmentally sustainable and efficient electric vehicles, thereby promoting the development of sustainable transportation systems.

Keywords: Electric vehicles, low temperature environment, energy flow, thermal system, vehicle test

NONMENCLATURE

Abbreviations	
PTC	Positive Temperature Coefficient
HVH	High Pressure Heater
IHX	Intermediate Heat Exchanger
OBC	On-Board Charger
PDU	Power Distribution Unit
MCU	Moter Control Unit
BMS	Battery Management System
HVAC	Heating, Ventilation and Air Conditioning

1. INTRODUCTION

As global energy demand continues to grow and climate change intensifies, the transition to sustainable energy systems has become one of the urgent challenges facing the world today. In this transition, electric vehicles (EVs) have garnered widespread attention as a clean and efficient alternative transportation option. However, challenges remain in the energy utilization efficiency and performance of electric vehicles under winter low-temperature conditions, which not only limit their applicability in cold climates but also hinder their global adoption and proliferation. Particularly, in real-world driving scenarios, there are significant discrepancies

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between battery energy consumption and laboratory test results, largely attributable to the operational state of thermal management systems (TMS), including the air conditioning system. Therefore, gaining a deep understanding of the energy flow distribution and energy utilization of electric vehicles under low-temperature conditions is crucial for optimizing their performance and enhancing their environmental sustainability.

In the current research context, numerous scholars have conducted extensive studies to deepen the understanding of energy consumption characteristics of electric vehicles (EVs) in low-temperature environments and to seek effective pathways for optimizing their performance. Seokbin Hong [1] developed a 1-D Vehicle Thermal Management simulation model for EVs to optimize vehicle efficiency and validate performance. Zhang [2] developed a comprehensive thermal management model for pure EVs to optimize energy efficiency and driving range, particularly in low-temperature conditions. Xie [3] evaluated the effects of driving and environmental variables on vehicle energy consumption and driving range using a simulation model based on energy flow analysis Zhang Yan [4] analyzed the effect of temperature on energy transmission in PHEVs, revealing significant impacts of SOC on generator losses. Feng [5] conducted an energy flow analysis on a hybrid EV, proposing two optimized control strategies that significantly reduce fuel consumption and enhance overall powertrain efficiency. Zhao [6] demonstrated the significant impact of environmental temperature on battery energy transmission by model, especially the effect on energy loss and battery SOC. Zhou et al. [7] conducted segmented driving energy consumption tests in cold environments, providing an in-depth exploration of the performance of electric vehicles under low-temperature conditions. Selvin Raj et al. [8] explored cooling strategies and power rating for electric vehicle motors, providing reference for motor selection in cold temperatures. Lian et al. [9] designed a vehicle thermal management control strategy based on dynamic programming, aiming to improve the driving range of pure electric vehicles in low-temperature environments while ensuring comfort. Wang et al. [10] developed an integrated vehicle model to investigate performance and energy distribution during cold starts, providing insights for optimizing energy distribution in vehicles.

In these studies, energy flow analysis methods have been widely applied to assess the energy consumption characteristics of EVs under various operating conditions, thereby providing important scientific foundations for optimizing vehicle energy management systems. However, due to the difficulties associated with conducting whole vehicle experiments and the complexity of interconnections within the vehicle's internal systems, few studies have explored and analyzed the entire vehicle energy flow of EVs, particularly under real-world driving scenarios in low-temperature conditions. Against this backdrop, the present study aims to delve into the energy flow distribution and consumption characteristics of EVs in low-temperature environments, with a particular focus on the energy consumption of various components when the air conditioning system is turned on or off under different low-temperature conditions. By employing the analytical method of whole vehicle energy flow, we conducted experimental tests and analyses of whole vehicle energy flow of a certain four-wheel-drive vehicle under different low-temperature conditions, thus filling the gap in previous research regarding the analysis of whole vehicle energy flow of EVs and providing profound understanding and effective guidance for the performance optimization and energy management of EVs in cold climates.

2. EXPERIMENTAL SETUP AND METHODS

2.1 Energy flow laboratory and the tested BEV

We have established a professional energy flow laboratory aimed at conducting in-depth research on the energy flow distribution and consumption characteristics of Battery Electric Vehicles (BEVs) under low-

Table 1 Main testing equipment and accuracies

Equipment	Calibrated range	Accuracy
Dynamometer	230 kW/h	/
Control/Data Acquisition Module	/	/
Current sensor	400 A/60 A	0.03 %
Voltage sensor	350 V/80 V	0.2 %
Pressure sensor	0-10 bar	0.2 %
	0-3 bar	0.2 %
Temperature sensor	0-300 °C	±0.15 °C
Power analyzer	1500 V/200 A	±0.1 %F.S
Distance measurement sensor	5000 ppr	±0.1 m/km
Speed measurement sensor	5000 ppr	±0.02 km/h
Acceleration measurement sensor	5000 ppr	±0.03 km/h
Torque sensor	5000 Nm	±0.05 %F.S

temperature conditions. The laboratory is equipped with advanced testing equipment and tools to ensure accurate recording and analysis of the entire vehicle energy flow data, and the specific equipment is shown in Table 1, while Figure 1 illustrates the scene of this laboratory, and the vehicles being tested.

Fig. 1 Vehicle Energy flow laboratory and the tested vehicle

A domestically excellent Multi-Purpose Vehicle (MPV) has been selected as the tested vehicle. This MPV features a flexible spatial layout and high load-bearing capacity, which better reflects the energy flow distribution and consumption characteristics of electric vehicles in real driving scenarios. With outstanding technical parameters and performance, this vehicle is a suitable choice for our experiment. The energy flow path of this vehicle is depicted in Figure 2, while the main vehicle technical parameters are detailed in Table 2.

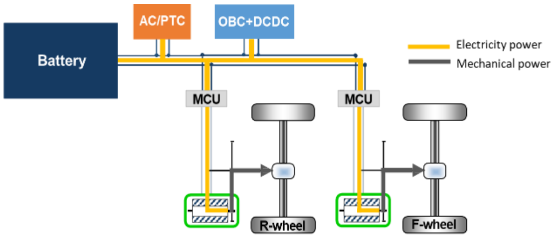


Fig. 2 The whole vehicle energy flow of a certain four-wheel drive vehicle

Table 2 Main technical parameters of the tested vehicle

Parameter	Value
Curb Weight (kg)	2620
Number of Drive Motors	2
Max Power of Front (Rear) Motors (kW)	160
Max Torque of Front (Rear) Motors (N.m)	310
Battery Type	Lithium-ion (ternary)
Battery Capacity (kW.h)	82
Max External Discharge Power (kW)	3.3

2.2 Experimental scheme and sensor arrangement

To investigate the energy flow distribution and consumption characteristics of electric vehicles in low-temperature environments, we devised experiments representative of -7 °C and -20 °C scenarios, which included variations with and without the activation of the air conditioning (HVAC) system to explore its impact on energy consumption within the thermal management system. Specifically, prior to the experiment, environmental chamber temperatures were set to -7 °C and -20 °C, with relative humidity at 10 %, no illumination, and zero wind speed. Additionally, the vehicle was immersed in this environment for 12 hours. Upon commencement of the experiment, environmental chamber conditions remained unchanged, but the dynamometer was activated. Furthermore, for the experiment of turning on air conditioning system, we initiated the vehicle's internal air conditioning system (in AUTO mode) with a temperature setpoint of 22 °C, utilizing the recirculation mode and foot vent mode. Subsequently, experimenters drove the vehicle according to the CLTC-P x1 driving cycle and collected relevant data throughout the experiment. Upon completion, experimenters exited the vehicle, concluding the experiment and halting data collection.

In order to assess the operational performance of the tested Battery Electric Vehicle (BEV) under road conditions, the Chinese Passenger Car Driving Cycle (CLTC-P) was selected as the tested cycle, as shown in Figure 3. And to ensure accurate recording of performance parameters for vehicle components, we designed a sensor arrangement scheme during the experiment. Specifically, Figures 4, 5 illustrate the sensor arrangement scheme of the power transmission system and the thermal management system, respectively.

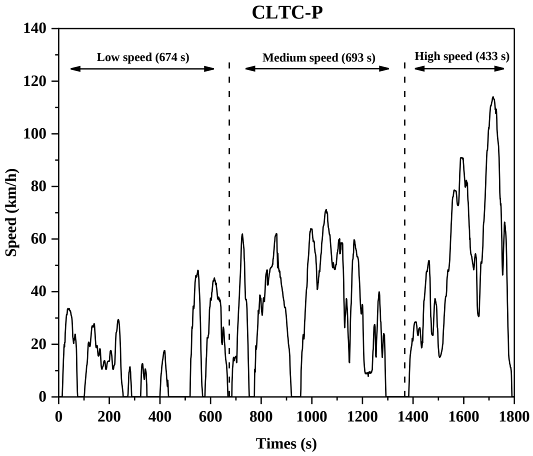


Fig. 3 China light-duty vehicle test cycle-passenger

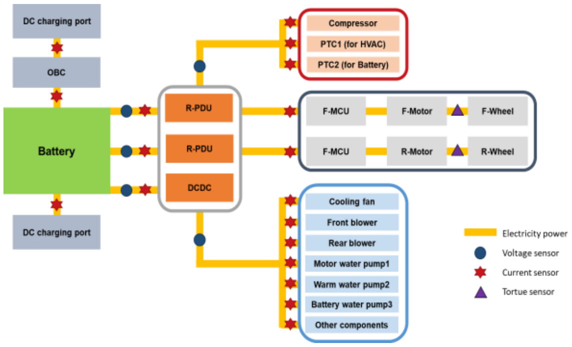


Fig. 4 Sensor arrangement scheme of vehicle power transmission system

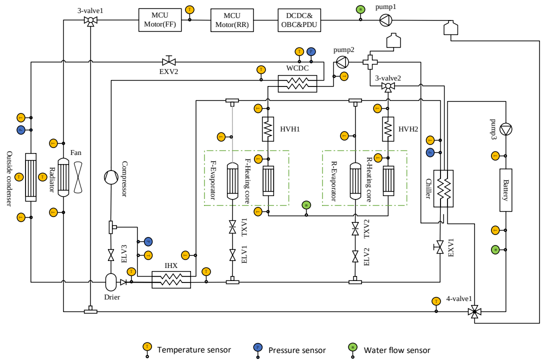


Fig. 5 Sensor arrangement scheme of vehicle thermal management system

3. RESULTS AND DISCUSSION

3.1 Vehicle energy flow analysis under low-temperature driving conditions

In this section, we conducted experiments under low-temperature conditions, specifically -7 °C and -20 °C, with and without air conditioning activated, using the Chinese Light-Duty Vehicle Test Cycle (CLTC-P). Figure 6 illustrates the battery output power curves under different conditions during the CLTC-P test, vividly portraying the differences in energy consumption curves with and without air conditioning. Particularly at -20°C, there is a noticeable suppression in battery output power, coupled with reduced energy recovery compared to -7°C, leading to further energy consumption.

Moreover, Figure 7 presents the overall vehicle energy consumption under the four experimental conditions, while Figure 8 shows the total energy consumption at three speed interval of CLTC-P test. Overall, compared to the standard energy consumption of 2.5 kW.h, energy consumption increased by 148.03 %, 188.83 %, 226.04 %, and 287.65 % for experimental conditions of -7 °C_HVAC_off, -7 °C_HVAC_on, -20 °C_HVAC_off, and -20 °C_HVAC_on, respectively. Correspondingly, the range decreased by 59.68 %, 65.38 %, 69.33 %, and 74.20 %, resulting in ranges of only 191.51 km, 164.45 km, 145.69 km, and 122.53 km, respectively.

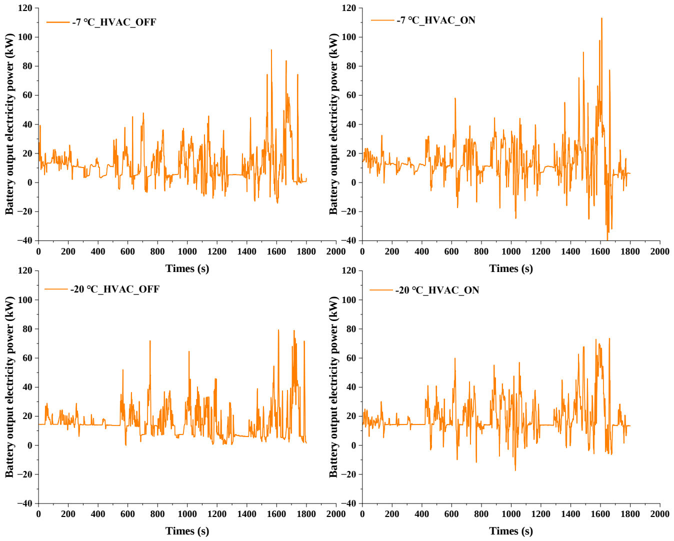


Fig. 6 Battery output electricity power curve (CLTC-P test)

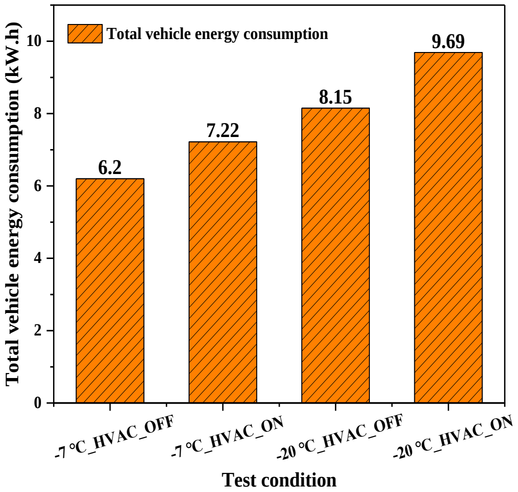


Fig. 7 Total energy consumption of the tested vehicle

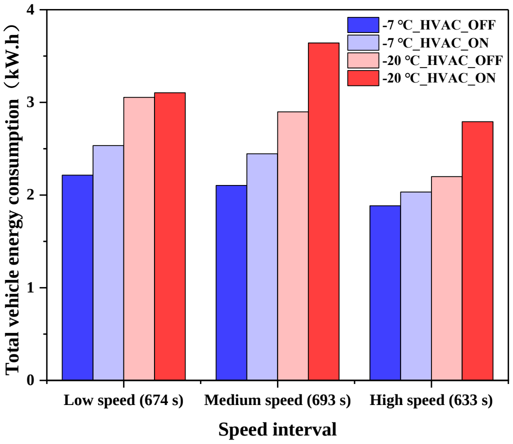
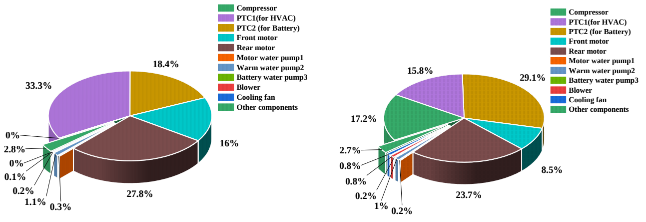
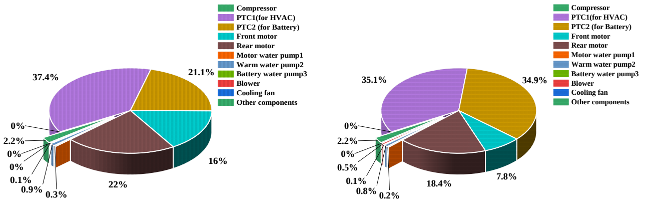


Fig. 8 Total energy consumption at three speed

Additionally, Figure 9 illustrates the proportion of power consumption among the main components of the vehicle system. It is evident that under low-temperature conditions, the power consumption of the PTC heater accounts for the highest proportion, primarily due to the thermal management requirements of the cabin and battery. Specifically, the proportions of PTC power consumption are 51.7 %, 44.9 %, 58.5 %, and 70.0 % for different experimental conditions, significantly exceeding the power consumption of the front and rear motors in the powertrain system (43.8 %, 32.2 %, 38.0 %, and 26.2 %, respectively). Particularly noteworthy is the scenario where the air conditioning system is activated, where the combined proportion of the compressor and PTC heater reaches 62.1 % at -7 °C. In contrast, at -20 °C, where the air conditioning compressor cannot operate, the PTC heater is solely responsible for providing heat to the cabin and battery, accounting for a staggering 70.0 % of total power consumption.



(a) -7 °C_HVAC_off *(b) -7 °C_HVAC_on*



(c) -20 °C_HVAC_off *(d) -20 °C_HVAC_on*

Fig. 9 Proportion of power consumption of components

3.2 Thermal management system energy flow analysis under low-temperature driving conditions

This section aims to analyze the energy consumption performance of various subsystems, with a particular focus on the thermal management system's energy distribution. Firstly, regarding the battery thermal management system, Figure 10 illustrates the energy consumption under four experimental conditions, measured at 3.30 kWh, 3.33 kWh, 4.87 kWh, and 4.04 kWh, respectively. It is noteworthy that under -20 °C conditions, the energy consumption of the battery thermal management system generally increases, with an increase of 47.58 % and 22.42 % compared to -7 °C. In experiments where the air conditioning is activated at -20°C, the heating power of PTC heater is limited, leading to insufficient heating power for the battery thermal management system, which explains the lower energy consumption compared to conditions without air conditioning.

Furthermore, from the battery temperature heating characteristic curve shown in Figure 11, we can observe the temperature rise speed and performance between the average temperature and the lowest temperature. Since the overall discharge performance of the battery is determined by the worst-performing battery cells, this also explains the reduced discharge performance of the battery at -20 °C compared to -7 °C conditions.

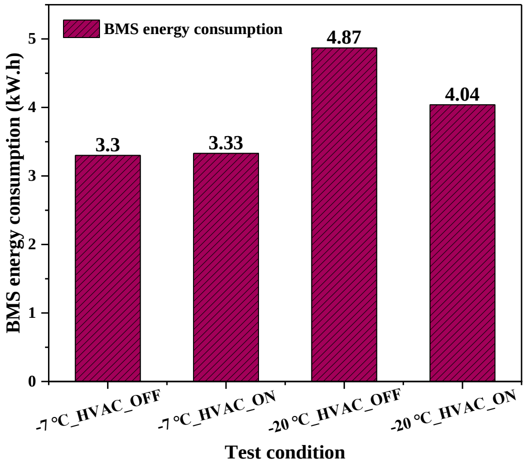
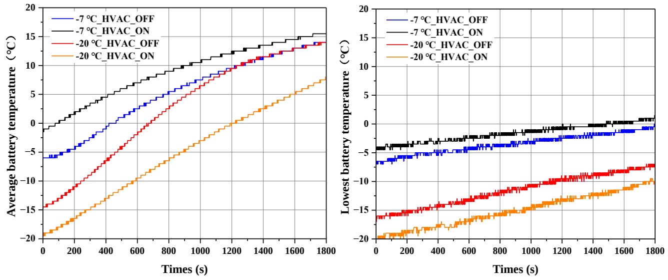


Fig. 10 BMS energy consumption



(a) Average temperature *(b) Lowest temperature*

Fig. 11 Battery temperature heating characteristic curve

Additionally, Figure 12 illustrates the energy consumption performance of each subsystem. It is noteworthy that, compared to the propulsion system, the thermal management system accounts for 54.00%, 65.76%, 59.82%, and 79.43% of total energy consumption under different experimental conditions. Moreover, under -7 °C and -20 °C conditions, activating the cabin thermal management system requires an additional energy consumption of 16.60 % and 18.44 %, respectively.

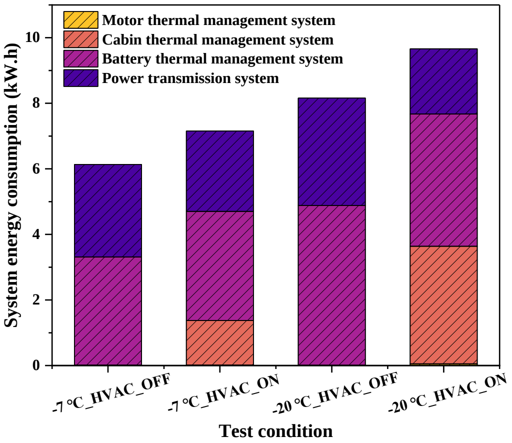


Fig.12 Total energy consumption of different subsystems

4. CONCLUSIONS

In conclusion, this study comprehensively investigated the energy flow characteristics and consumption patterns of electric vehicles (EVs) under low-temperature conditions, with a particular focus on the impact of the thermal management system (TMS).

The main findings of our study can be summarized as follows:

1. Vehicle Energy Consumption Analysis: Our research revealed a significant increase in EV energy consumption under low-temperature conditions, Notably, the energy consumption surge is more pronounced when the air conditioning is activated at -20 °C, compared with the standard working condition, with energy consumption increasing by up to 287.65 % corresponding to a 74.20 % decline in driving range.

2. Major Component Power Consumption: Under low-temperature conditions, the power consumption proportion of PTC heaters significantly increases, especially at -20 °C. When the air conditioning is activated, the power consumption proportion of PTC heaters reaches as high as 70.0 %, making a significant contribution to the total energy consumption.

3. Thermal Management System Energy Consumption: We found that the energy consumption of the battery thermal management system substantially increases under low-temperature environments, particularly at -20 °C, with an increase of 47.58 %, (compared to -7 °C) primarily due to the increased demand for battery heating.

4. Subsystem Energy Comparison: The energy consumption proportion of the thermal management system significantly increases under different experimental conditions, especially in low-temperature environments. Additionally, activating the cabin thermal management system incurs an additional energy consumption ranging from 16.60 % to 18.44 %.

In summary, this study underscores the importance of optimizing the thermal management system in EVs to enhance energy efficiency and promote sustainable mobility in the face of increasingly severe climate challenges. By addressing the challenges posed by low-temperature driving conditions, our research advances the development of sustainable transportation systems and paves the way for widespread adoption of EVs and the realization of a cleaner, greener future.

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