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Enhancing electric vehicle thermal management system with heat pump coupled phase change thermal storage unit#

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ABSTRACT

This study presents a technological advancement in electric vehicle (EV) heat pump systems by integrating a phase change thermal storage unit (PCTSU). This integration optimizes waste heat supply under real-world conditions, enabling efficient system operation in low-temperature environments and reducing the risk of frost formation on the external heat exchanger. Analysis based on a 1D system simulation model shows that even at an ambient temperature of -10 °C, the system with PCTSU achieves a coefficient of performance (COP) exceeding 1.8, indicating an approximately 22% improvement in energy efficiency compared to the original system. Additionally, the PCTSU reduces the thermal load on the external evaporator, contributing to maintaining normal system operation in cold climates. Under various driving conditions, the PCTSU-enhanced system demonstrates higher COP and more stable thermal load distribution. PCTSU shows potential in enhancing the thermal performance and efficiency of EV heat pump systems.

Keywords: electric vehicle, thermal management system, heat pump, phase change thermal storage unit

NONMENCLATURE

Abbreviations	
COP	Coefficient of Performance
EV	Electric Vehicle
NEDC	New European Driving Cycle
PCM	Phase Change Materials
PCTSU	Phase Change Thermal Storage Unit
PTC	Positive Temperature Coefficient
TMS	Thermal Management System
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

1. INTRODUCTION

Electric vehicle (EV) has rapidly advanced due to their low emissions and high energy efficiency. However, range anxiety remains a significant challenge, particularly under adverse weather conditions[1]. The limited space available in vehicles, along with the cost and weight of batteries, restricts the number of batteries that can be installed, thereby limiting the driving range[2]. Addressing this issue requires improving energy consumption and enhancing energy utilization efficiency. The energy consumption of the cabin thermal management system (TMS) is notably high, especially during winter[3]. Unlike conventional internal combustion engine vehicles, EV lack sufficient waste heat to directly provide heating to the cabin.

Positive Temperature Coefficient (PTC) is widely used for cabin air heating[4]. However, PTCs have low energy efficiency, which can reduce the driving range of EV by approximately 50% to 60%[4, 5]. Heat pump technology, with its high efficiency, environmental benefits, and cost-effectiveness, offers a promising solution to this problem[6]. Zhang et al.[7] found that, compared to EV equipped with PTCs, the adoption of a heat pump system with an average Coefficient of Performance (COP) of 1.7 increased the vehicle's driving range by 7.6% to 21.1%. Additionally, Zhang et al.[8] calculated the annual total energy consumption of EV air conditioning systems in various Chinese cities, and discovered that heat pump systems have the highest operating efficiency in mid-latitude regions, with an average energy saving of 41.3% compared to PTC.

However, conventional direct heat pump systems suffer from frost formation issues in low-temperature climates, which can reduce the COP by 30% to 60%[9]. In some cases, frost can even prevent the heat pump

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system from operating[10, 11]. At temperatures below -20 °C, the performance of heat pumps can be inferior to that of PTC heaters[12]. To address this issue, Pomme et al.[13] introduced an improved heat pump system that utilizes waste heat from the battery and motor as auxiliary heat sources. This system demonstrated a 15% reduction in electrical energy consumption compared to PTC heaters at -10 °C. Additionally, Tian et al.[14] proposed a TMS that incorporates motor waste heat recovery. Their study investigated the effects of compressor speed, ambient temperature, and waste heat recovery on the TMS's performance. The results indicated that waste heat recovery enhances system performance, with the COP increasing by 25.55% as the recovered heat increased from 0 to 1000 W.

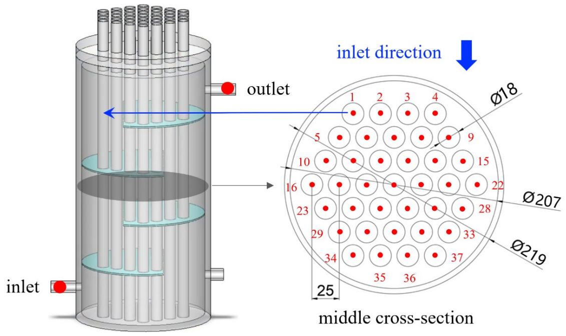
Existing studies on the integration of heat pumps with auxiliary systems in EV, whether experimental (e.g., ref[9]) or simulation-based (e.g., ref[14]), typically utilize a constant heat input to the heat pump system to assess its performance and efficiency. However, in real-world EV operation, the amount and rate of waste heat generated by the motor can vary significantly due to factors such as driving conditions and ambient temperature, leading to considerable fluctuations.

In this study, we proposed a novel technological solution for EV heat pump systems by integrating a phase change thermal storage unit (PCTSU). This approach addresses the discrepancies in quantity, form, and timing of waste heat availability during real-world EV operation, allowing the heat pump system to function effectively in low-temperature environments. The PCTSU was designed to meet the thermal management requirements of EV cabins. Furthermore, a 1D system simulation model of the electric vehicle thermal manage-ment system with a heat pump coupled PCTSU was developed, revealing the impact of PCTSU on system performance under various driving and environmental conditions.

2. METHODOLOGY

2.1 PCTSU design

The PCTSU adopts a shell-and-tube structure, with phase change materials (PCM) filled inside the tubes, as detailed in Figure 1(a). The cross-section at the middle section of the inner tubes is shown in Figure 1(b). Detailed geometric parameters of the PCTSU are provided in Table 1.



(a) *(b)*

Fig.1 The structure of phase change thermal storage unit. (a) Temperature measurement on the water side; (b) Middle cross section of temperature measurement on the PCM side.

Table 1 Geometry parameters of PCTSU

Item	Dimensions and descriptions	Unit
Shell-side (water)		
l_w	500	mm
$d_{w,i}$	207	mm
$d_{w,o}$	219	mm
Tube-side (PCM)		
l_P	500	mm
$d_{P,i}$	16	mm
$d_{P,o}$	18	mm
Tube pinch p_t	25	mm
Number of tubers	37	——
Baffle		
Pinch p_b	100	mm
Height	127	mm
Thickness	3	mm
Material	Stainless steel	——

2.2 Materials and performance characterization

The PCTSU designed in this study aims to recover waste heat generated by electric vehicle thermal management system (EVTMS), positioned within the motor circuit. The thermal management requirement for the motor is to maintain temperatures below 80 °C. Considering the impact of heat transfer differentials, paraffin with a phase change temperature of 58 °C was selected as the heat storage material. Due to the low thermal conductivity of pure paraffin, expanded graphite was chosen as the thermal conductor. The specific thermophysical parameters of the composite meterials are listed in Table 2.

Table 2 Thermophysical parameters

Item	Value	Unit
Density	800	kg/m^3
Solidification temperature	58.52	°C
Melting temperature	54.81	°C
Latent heat	178.35	kJ/kg
Thermal conductivity (solid)	2.22	W/(m·K)
Thermal conductivity (liquid)	1.75	W/(m·K)

3. SIMULATION

3.1 *Design description*

Figure 2 shows the schematic diagram of EVTMS with heat pump coupled PCTSU. The basic heat pump system consists of a compressor, an internal condenser, an external evaporator, and an expansion valve, as indicated by the blue lines in Figure 2. The refrigerant is R134a. The PCTSU was located in the motor cooling circuit, specifically at the motor outlet, and serves to recover waste heat. The coolant was 50% ethylene glycol aqueous solution. The PCTSU was connected in series with a plate heat exchanger, whtableich transfers the recovered waste heat from the motor cooling circuit to the heat pump system.

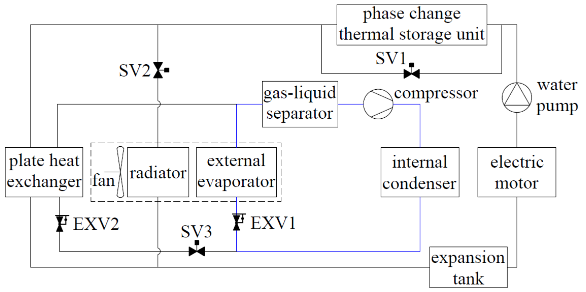


Fig.2 Schematic diagram of electric vehicle thermal management system with heat pump coupled phase change thermal storage unit.

3.2 *Modeling*

In this study, a 1D system simulation model of the EVTMS with heat pump coupled PCTSU was developed, which includes the EV, PCTSU, and other key components. The simulation is based on the specifications of a Class A EV, with the parameters listed in Table 3.

Table 3 Electirc vehicle parameters

Item	Value	Unit
Vehicle mass	1080	kg
Cabin volume	2.8	m^3
Battery capacity	22.4	kWh
Motor maximum power	52	kW

The main component parameters of heat pump are listed in Table 4.

Table 4 Heat pump component parameters

Components	Parameters	Remarks
Compressor	34 cc/r. 1000-6000 rpm	Scroll compressor
External evaporator	624×325×32 mm	Microchannel parallel flow heat exchanger
Internal condenser	230×210×26 mm	

3.3 *Operating Conditions*

This study compares two EVTMS: one with the addition of PCTSU and one without PCTSU (i.e., the original vehicle's heat pump system without heat recovery), analyzing their performance under various operating conditions. Both systems were configured with the same control strategy, using a proportional-integral-derivative controller to adjust the compressor speed with the goal of maintaining the cabin temperature around 22 °C. The COP calculation is provided in Equation (1).

$$COP = \frac{Q_{con}}{W} \tag{1}$$

Where Q_{con} and W refers to the heat exchange capacity of the internal condenser and compressor power consumption, respectively.

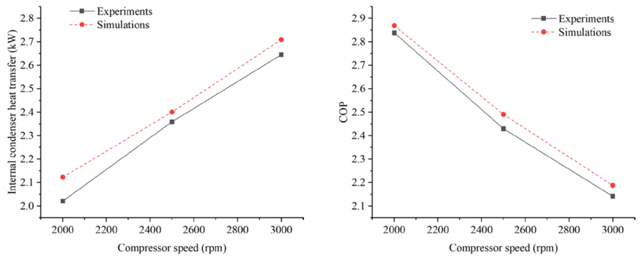
The operating conditions are categorized into two types: driving conditions and environmental conditions. For driving conditions, the ambient temperature was set to 5 °C, and three constant speed scenarios were studied: 40 km/h, 80 km/h, and 120 km/h. Additionally, two cycle conditions were examined: the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light Vehicles Test Cycle (WLTC). Environmental conditions included ambient temperature of -10 °C, -5 °C, 0 °C, 5 °C, and 10 °C. The system operation duration was set to 3600 s, with a calculation step of 1 s.

3.4 *Validation*

For the basic heat pump system, the experimental test conditions were as follows: compressor speeds of 2000 rpm, 2500 rpm, and 3000 rpm; indoor side dry and wet bulb temperatures set at 20 °C/15 °C with an airflow rate of 350 m^3/h; and outdoor side dry and wet bulb temperatures set at 7 °C/6 °C with an airflow rate of 500 m^3/h.

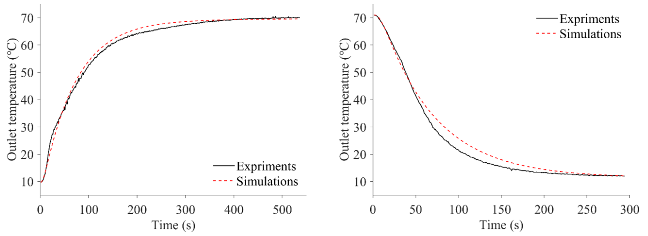
Figure 3 compares the predicted heat transfer rate of the internal condenser with the experimentally measured values. The results indicate that for the tested compressor speeds, the average deviation between the simulated and experimental values for the internal condenser heat transfer rate is 3.08%, while the average deviation for the system COP is 1.92%.

For the PCTSU, Figure 4 compares model predictions and experimental measurements of temperatures during the charging and discharging processes of the PCTSU. The results indicate that the predicted outlet temperatures closely match the experimental measurements during both the charging and discharging.



(a) *(b)*

Fig.3 Comparison of model predictions with experimental data for the basic heat pump system. (a) Internal condenser heat transfer; (b) COP.



(a) *(b)*

Fig.4 Comparison of model predictions with experimental data for the PCTSU. (a) Charging; (b) Discharging.

4. RESULTS AND DISCUSSION

4.1 Performance enhancement of EVTMS with PCTSU under different ambient temperature

Figure 5 presents the cabin temperature of EV with original system and PCTSU at various ambient temperature. The results indicate that, under the current control strategy, the cabin temperature is stabilized at approximately 22 °C across all operating conditions. The ambient temperature affects the time required for the cabin temperature to reach steady state. Higher ambient temperatures lead to a shorter stabilization period. This suggests that the thermal response of the cabin is faster in warmer environments, which could be attributed to the reduced heat load and more efficient operation of the heat pump system under these conditions.

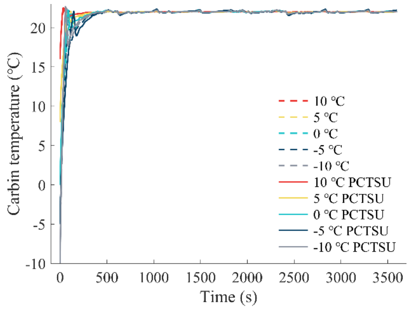


Fig.5 Cabin temperature of EV with original system and PCTSU at various ambient temperature.

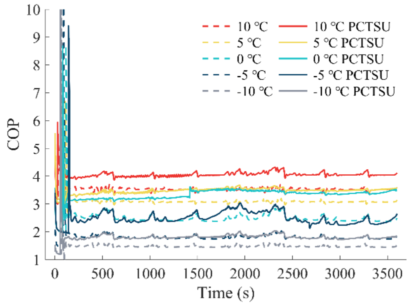


Fig.6 COP of heat pump with original system and PCTSU at various ambient temperature.

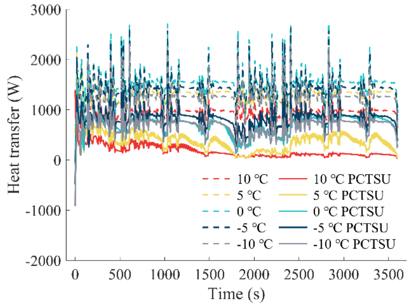


Fig.7 Heat transfer of the external evaporator with original system and PCTSU at various ambient temperature.

Figure 6 shows the COP of the heat pump system, comparing the original system with the one integrated with PCTSU under various ambient temperatures. The results indicate that ambient temperature significantly impacts the COP. Under the same ambient temperature, the COP of the heat pump system with PCTSU is substantially higher compared to the original system. Even at an ambient temperature of -10 °C, the COP remains above 1.8, indicating an approximate 22% improvement in energy efficiency due to the integration of PCTSU. Figure 7 shows the heat transfer of the external evaporator with the original system and PCTSU at various ambient temperatures. The addition of PCTSU significantly reduces the load on the outdoor heat exchanger in the original system. This reduction in load helps mitigate the risk of frost formation, ensuring more stable and efficient system operation in cold climates.

4.2 Performance enhancement of EVTMS with PCTSU under different driving conditions

Figure 8 presents the cabin temperature of the EV equipped with both the original system and the PCTSU under various driving conditions. It can be observed that the cabin temperature stabilizes rapidly around 22 °C across all driving conditions. The nearly overlapping steady-state curves indicate that the driving conditions have little to no impact on the stability of the cabin temperature.

Figure 9 illustrates the COP of the heat pump system, comparing the original system with the one integrated with PCTSU under various driving conditions. The results demonstrate that the inclusion of PCTSU significantly enhances COP across all tested conditions, with a more noticeable improvement at higher speeds, particularly at 120 km/h. This suggests that PCTSU's thermal storage becomes increasingly effective as heat demand rises. Additionally, under standard driving cycles like NEDC and WLTC, the PCTSU system maintains greater COP stability with reduced fluctuations, ensuring reliable thermal performance and energy efficiency across varying driving conditions. The sharp COP increase at 120 km/h after 2500 s further underscores PCTSU’s effectiveness in maintaining thermal balance under high energy demands, optimizing the heat pump system’s efficiency in winter conditions. Figure 10 shows the heat transfer of the external evaporator with the original system and PCTSU at various driving conditions. The results indicate that the addition of PCTSU significantly reduces the thermal load on the outdoor heat exchanger across all driving conditions. Notably, the heat transfer rates in the PCTSU system show less fluctuation and a more stable pattern compared to the original system. This reduction in load is particularly evident at higher speeds, such as 120 km/h. This suggests that integrating PCTSU can enhance the efficiency and stability of the heat pump system across various driving conditions.

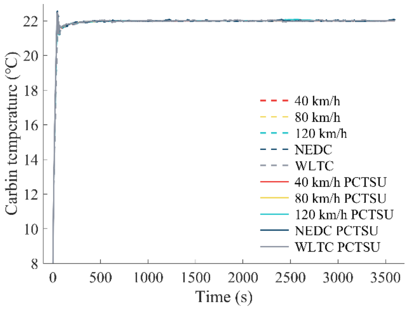


Fig.8 Cabin temperature of EV with original system and PCTSU at various driving condition.

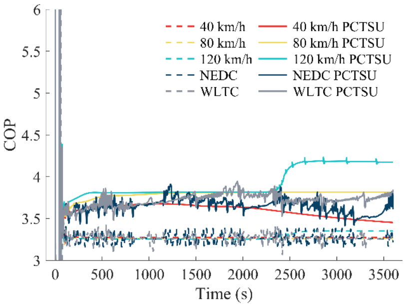


Fig.9 COP of heat pump with original system and PCTSU at various driving condition.

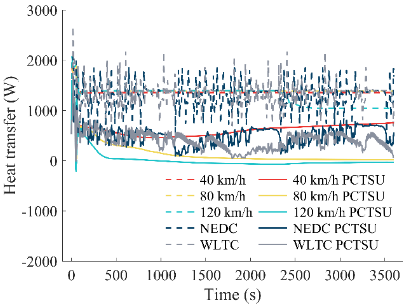


Fig.10 Heat transfer of the external evaporator with original system and PCTSU at various driving condition.

5. CONCLUSIONS

This study presents a novel technology for electric vehicle (EV) heat pump systems that integrates a phase change thermal storage unit (PCTSU) to address the mismatch in quantity, form, and timing of waste heat availability during real-world EV operation.

The 1D system simulation model reveals that PCTSU impacts the performance of the EVTMS under various ambient temperatures and driving conditions. Even at an ambient temperature of -10 °C, the Coefficient of Performance (COP) of the system with PCTSU remains above 1.8, indicating an approximate 22% improvement in energy efficiency compared to the original system. Additionally, the integration of PCTSU reduces the thermal load on the external evaporator, lowering the risk of frost formation and ensuring stable system operation, particularly in cold climates.

Under different driving conditions, the PCTSU system shows higher COP and more stable heat load distribution, especially at high speeds (120 km/h). This suggests that PCTSU enhances both the efficiency and stability of the system across various operating conditions.

In summary, the PCTSU proposed in this study demonstrates its potential impact on the thermal performance and overall efficiency of EV heat pump systems, offering a promising solution for managing EV thermal loads in low-temperature environments.

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