HEAT MANAGEMENT SYSTEM OF ELECTRIC VEHICLE BASED ON HEAT PUMP AND ENERGY RECOVERY OF REMOVABLE BATTERY

by

Yuanfei XUE[a,b]***, Xudong DIAO***[b]***, and Xin LI***[a*]

[a] Macau University of Science and Technology, Macau, China
[b] Shenzhen Polytechnic, Shenzhen, Guangdong, China

Original scientific paper
https://doi.org/10.2298/TSCI2302215X

In order to manage the air-conditioning thermal system, battery thermal system and motor thermal system in a unified manner, the author proposes a self-developed integrated thermal management system for electric vehicles to recover battery energy. Firstly, the problems in the development of electric vehicles and the importance of thermal management system are introduced, secondly, the self-developed thermal management system scheme and the principle of each part are analyzed, the experimental results of thermal system in enthalpy difference chamber are also introduced. The experimental results show that: Under the double evaporation system, when the compressor speed is 4500 rpm, the maximum COP is 2.46, and the maximum COP charge is 1180 g, the maximum heat transfer capacity is 4819 W (wind side heat transfer + water side heat transfer), the evaporation temperature is 5.35 °C, the evaporation superheat is 9.5 °C, the condensation temperature is 59.3 °C, the undercooling degree is 10.4 °C, the suction pressure is 280 kPa, and the exhaust pressure is 1694 kPa. In conclusion, the thermal management system has great energy saving effect, which ensures that the electric vehicle range will not be greatly attenuated under winter heating conditions, and meets the requirements of comfort.

Key words: *heat pump, electric vehicles, thermal management*

Introduction

With the continuous improvement of the level of industrial production technology and people's demand for intelligent electrical products, the automobile, as one of the embodiment of modern advanced industrial civilization, has become an indispensable part of people's production and life. However, the energy crisis and environmental pollution caused by traditional fuel vehicles, such as fossil fuel depletion, air pollution and greenhouse effect, have hindered the progress of world economy and the sustainable and stable development of society, and these problems will become more and more serious, so the new green energy vehicle has become the main development direction of the automobile industry. Compared with traditional fuel vehicles, pure electric vehicles use electric energy as the driving force and have the advantages of zero emission, low noise pollution and low operating cost, which has become one of the main trends in the development of the new energy vehicle industry. Electric vehicles have become a major player in the auto industry, the electric vehicle industry will continue to expand, with more than 100 million plug-in electric vehicles on the road worldwide by 2030. The state also attaches great importance to the development of the electric vehicle industry, on December 3,

[*] Corresponding author, e-mail: xinli71@163.com

2019, the Ministry of Industry and Information Technology publicly soli-cited comments on the Development Plan for the New Energy Vehicle Industry (2021-2035) (draft), and proposed to deepen the R and D lay-out of three vertical and three horizontal, increase the share of new-energy vehicles in sales to 25% by 2025 [1].

Literature Review

Wang *et al*. [2] pointed out that compared with PTC electric heating, R134a heat pump system was used for heating, the energy consumption of electric vehicles is reduced by 50% and the driving range is increased by 10-30%. Chen *et al*. [3] analyzed the heating performance of electric vehicle heat pump system through mathematical model, and the simulation results showed that the heating COP was >3.3, but no effective experimental verification was carried out. Peter *et al*. [4] studied the nominal heating condition stipulated in GB/T 7725-2004, the influence of compressor speed and fan motor speed on the heating performance of heat pump air conditioning system of electric bus, MATLAB and SIMULINK were used to establish the sub-models of each component of the electric vehicle variable frequency heat pump air conditioning system, and the steady-state simulation model of the whole air conditioning system was obtained through the coupling relationship between the sub-models, the trends of heat production, power consumption and COP with compressor speed and fan motor speed were analyzed. The simulation results show that, the speed of the two should be selected according to the environmental conditions to obtain a higher system energy efficiency ratio. Pirmohamadi *et al*. [5] conducted experimental research on the changes of ambient temperature and compressor speed on system pressure, exhaust temperature and cabin temperature with time during the start of heat pump system heating mode of pure electric vehicle. The results show that the higher the rotational speed of the compressor, the greater the system heat, and the shorter the time to reach the steady-state. The lower the ambient temperature, the lower the heat production capacity of the system, and the longer the time to reach steady-state.

Research methods

Design of heat pump electric air conditioning module

The self-developed heat pump type electric air conditioning module is composed of Japan three electric scroll type electric compressor, outer condenser, expansion valve, inner condenser, vapor-liquid separator, dryer filter, condensing fan, Danfoss electromagnetic valve and HVAC box (including evaporator and blower), these parts are outsourced and connected to form air conditioning modules [6].

Cooling mode

Similar to the traditional refrigeration mode, the electric compressor, the external condenser, the cooling fan, the liquid storage tank, and the HVAC box form a closed system. After the control system is started, the refrigerant is compressed by the scroll electric compressor, and the high pressure refrigerant dissipates the heat of the working medium to the atmospheric environment through the outer condenser, the refrigerant itself transforms from gaseous heat dissipation liquid, then through TVX1 step-down into the evaporator to absorb the heat in the cabin, so that the cabin to maintain temperature comfort [7, 8].

Heating mode

When the system controls the opening and closing of the two-way and three-way valves, the cooling mode can be converted to the heating mode. After the refrigerant is compressed by the scroll electric compressor, the high pressure working medium flows into the internal condenser of the HVAC box through the solenoid valve, and the blower radiates the heat of the refrigerant working medium into the crew compartment, and through the solenoid valve, the high pressure refrigerant is directed to the TVX3 installed on the outside side, and after the pressure is reduced, it enters the outside condenser to absorb the ambient air heat for evaporation. The heat emitted by the inner condenser increases the temperature in the crew compartment and maintains the temperature comfort in the crew compartment, fig. 1.

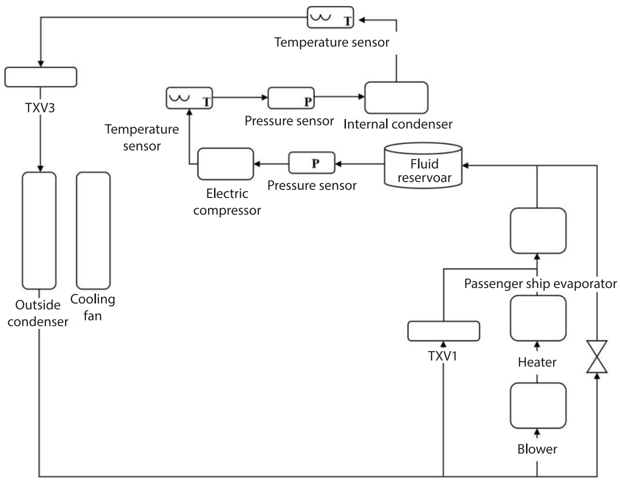

Figure 1. Heating mode of the electric air conditioner module

Design of power battery thermal management module

The power battery thermal management module consists of the following parts: compression refrigeration module, cooling tank cooling module, electronic circulation water pump, PTC heating module, expansion water tank*, etc.* The designed power battery thermal management module can be operated in three different modes: Compression cooling for high temperature cooling, air cooling for low temperature cooling by radiator, and PTC water heating for low temperature heating [9].

High temperature cooling mode. When the outlet temperature of the battery cold plate is high, compression refrigeration module is adopted, fig. 2, after the refrigerant is compressed by the scroll electric compressor, the heat of the refrigerant is released to the atmosphere through the outside air-cooled condenser, the high pressure refrigerant enters the evaporator in HVAC through TVX1 to absorb the heat in the crew cabin, and enters the plate evaporator through TVX2 to absorb the heat in the cooling water of the power battery cold plate.

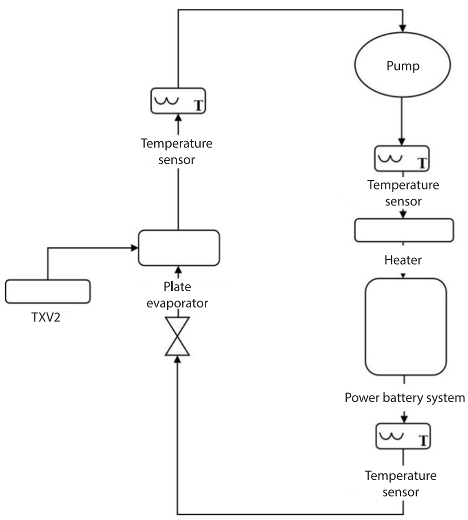

Figure 2. High temperature cooling mode of power battery

Design of power electronics cooling module

The design of power electronic cooling module is relatively simple, which is composed of cooling water tank, electronic circulating water pump, expansion water tank and so on. The cooling water of the main drive motor directly passes through the cooling tank, the cooling water is cooled by the cooling fan, and the cooling water is sent to the motor driving cooling water chamber through the electronic circulating water pump, the power electronic components are cooled first, and then the main motor body is cooled by the motor water chamber. The temperature at which cooling water enters the cooling water chamber of the power electronic component can be controlled by controlling the speed of the electronic circulating pump, fig. 3.

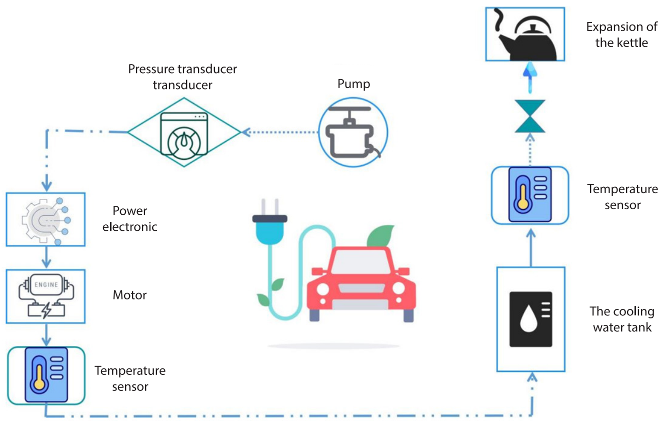

Figure 3. Power electronics cooling module

Operation parameter collection, monitoring and alarm of each module

In addition the aforementioned module's own controller, the design scheme also adds the integrated thermal management system control module. The control module receives the operation parameters of each module (air conditioning module, power battery module, power electronics cooling module) from the electric vehicle controller through CAN bus to collect, monitor and alarm, and sends control instructions according to the operation requirements [10].

The parameters to be monitored by the control module of the integrated thermal management system are shown in tab. 1.

Result analysis

After the aforementioned submodules and control system are built, it is necessary to carry out the test of the integrated thermal management system to verify the system performance designed by ourselves. The performance coefficient COP value was tested under cooling and heating conditions, as well as the system performance under defrosting conditions. COP is calculated:

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

where Q is the heat exchange of the condenser and P – the input power.

The 55 kW comprehensive enthalpy difference laboratory of the experimental center of a company was specially commissioned to carry out the experiment. The heat transfer and wind resistance of evaporator and internal condenser were measured by air enthalpy difference method. The heat generated by battery is simulated by constant temperature water tank circulation system, and the heat is exchanged with refrigerant by plate heat exchanger [11].

Table 1. Parameters to be monitored by the system control module

Primary parameter	The secondary parameters	Level 3 parameters
System operating parameters	Heat pump type electric air conditioning module	The environment temperature
		Compressor high pressure
		Compressor low pressure
		Compressor temperature protection
		Compressor operating current
		Compressor working speed
		Working current of the condensing fan
		Blower operating current
		Evaporator inlet temperature
		Evaporator inlet temperature
		External evaporator (heating) temperature
		Inlet air temperature of inner condenser
		Power battery water outlet temperature
		Pump operating current
	Power battery thermal management module	Outlet water temperature of plate evaporator
		Water tank outlet temperature
		PTC temperature control
	Main drive motor cooling module	Motor cooling outlet water temperature
		Pump operating current
	Cooling module for power electronic components	Cold plate outlet water temperature
		Pump operating current
The system alarm	Heat pump type electric air conditioning module	Compressor high pressure alarm
		Compressor low pressure alarm
		Compressor overcurrent alarm
		Compressor temperature protection alarm
	Water pump outlet pressure alarm module	Water pump overcurrent alarm
		The condensing fan exceeds the current alarm
		PTC overtemperature alarm
		Power battery water outlet temperature alarm
		Pump working current alarm
	Power battery thermal management module	Outlet water temperature of plate evaporator
		Water outlet temperature alarm of water tank
		Cooling module for power electronic components
		Cold plate outlet water temperature alarm
		Pump working current alarm

The air enthalpy difference method is a method to determine the refrigeration and heating capacity of the air conditioner, it measures the supply air parameters, return air parameters and circulating air volume of the air conditioner, and determines the capacity of the air conditioner by the product of the measured air volume and the supply air and return air enthalpy difference.

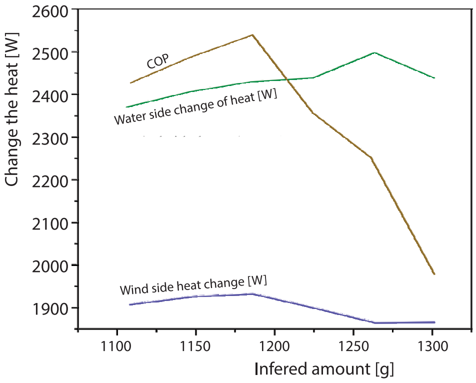

Figure 4. Variation trend of performance coefficient with charging amount

Refrigeration condition test

Under the double evaporation system, under the refrigeration condition with the speed of the electric compressor at 4500 rpm, the heat transfer trend of the wind side and water side and the COP of the system change with the charging amount are shown in fig. 4 below [12, 13].

Heating condition test

Through the control algorithm program to control the solenoid valve on and off, the operation mode of the heat pump system test bench can be switched to the heating mode, if the speed of the compressor is relatively high in the test, the evaporation pressure will be lower, and the inspiratory capacity of the refrigerant will increase, the suction volume of the unit decreases, the capacity of the compressor decreases, thus reducing the heat production, and the pressure ratio of the compressor increases, the performance coefficient of the system is relatively low, so in the heating mode, the compressor speed selected in the actual test is 2000 rpm and 3000 rpm. The test results are shown in fig. 5.

Defrosting condition test

According to the requirements of the experimental plan, under the defrosting condition, it should be stable for more than three defrosting cycles. According to the inspiratory pressure and defrosting temperature, the defrosting conditions can be judged Switch the heating mode to refrigeration mode, turn off the outdoor heat exchanger fan, until the frost layer on the surface of the outdoor heat exchanger melts away, open the outdoor fan, the air volume is adjusted to 75% of the maximum air volume, blow water on the outdoor heat exchanger for 1 minute. In the process of defrosting experiment, the variation curve of inspiratory pressure and outdoor unit

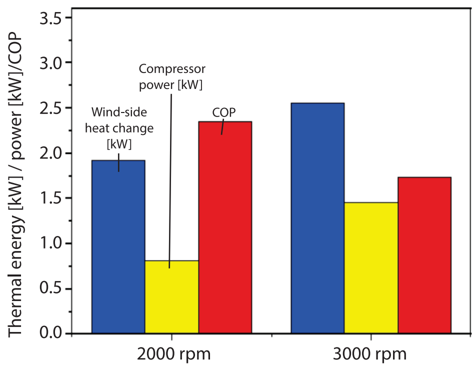

Figure 5. Performance diagram of the system at two different rotational speeds

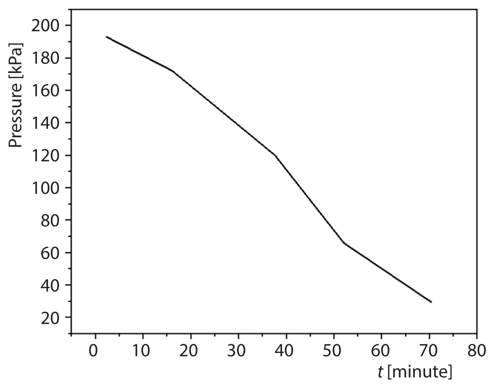

Figure 6. Variation curves of suction pressure and evaporator outlet temperature with time

outlet temperature with time, the frosting time was 71 minutes, and the defrosting time + water blowing time was about 5 minutes [14, 15], fig. 6.

Conclusion

According to the test results, compared with the traditional vehicle air conditioning system, the self-designed integrated thermal management system platform in the enthalpy difference room test, the electric air conditioning system cooling when the COP is 2.46, heating when the COP is 2.37. However, ordinary electric vehicles are cooled by single cooling system in summer and heated by electric heating system in winter, the COP value of electric heating system is 1.0. It can be seen that the integrated thermal management system, under the heating condition, compared with ordinary electric vehicles that rely on electric heating alone, the energy efficiency ratio of the integrated thermal management system of new energy electric vehicles is more than two times that of the PTC heating system, it has great energy saving effect, and ensures that the electric vehicle range will not be greatly attenuated under winter heating conditions, so as to meet the needs of consumers.

Reference

[1] Gilani, H. A., *et al*., Performance Analysis of Integrated Solar Peat pump VRF System for the Low Energy Building in Mediterranean Island, *Renewable Energy*, *174* (2021), 8, pp. 1006-1019
[2] Wang, D., *et al*., Experimental Investigation of a Part Air Dehumidification Cascade-Like Heat Pump Drying System, *International Journal of Refrigeration*, *131* (2021), 2, pp. 235-243
[3] Chen, Y., *et al*., Integrated Performance Analysis of a Space Heating System Assisted by Photovoltaic/Thermal Collectors and Ground Source Heat Pump for Hotel and Office Building Types, *Renewable Energy*, *169* (2021), 7, pp. 925-934
[4] Peter, M., *et al*., Computational Intelligence and Mathematical Modelling in Chanterelle Mushrooms' Drying Process under Heat Pump Dryer, *Biosystems Engineering*, *212* (2021), 8, pp. 143-159
[5] Pirmohamadi, A., *et al*., Exergoeconomic Analysis of a Novel Hybrid System by Integrating the Kalina and Heat Pump Cycles with a Nitrogen Closed Brayton System, *Energy Reports*, *7* (2021), 1, pp. 546-564
[6] Ryu, H. H., *et al*., Reducing Cobalt from Lithium-Ion Batteries for the Electric Vehicle Era, *Energy and Environmental Science*, *14* (2021), 2, pp. 844-852
[7] Hardman, S., *et al*., A perspective on Equity in the Transition Electric Vehicle, *MIT Science Policy Review*, *2* (2021), 7, pp. 46-54
[8] Verma, S., *et al*., A Comprehensive Review on Estorage in Hybrid Electric Vehicle, *Journal of Traffic and Transportation Engineering (English Edition)*, *8* (2021), 5, pp. 621-637
[9] De Klerk, M. L., Saha, A. K., A Comprehensive Review of Advanced Traction Motor Control Techniques Suitable for Electric Vehicle Applications, *IEEE Access*, *9* (2021), 7, pp. 125080-125108
[10] Khalid, M. R., *et al*., A Comprehensive Review on Structural Topologies, Power Levels, Energy Storage Systems, and Standards for Electric Vehicle Charging Stations and Their Impacts on Grid, *IEEE Access*, *9* (2021) 2, pp. 128069-128094
[11] Ahmad, F., *et al*., Optimal Location of Electric Vehicle Charging Station and Its Impact on Distribution Network: A Review, *Energy Reports*, *8* (2022), 2, pp. 2314-2333
[12] Kannan, C., *et al*., Critical Review Towards Thermal Management Systems of Lithium-Ion Batteries in Electric Vehicle with Its Electronic Control Unit and Assessment Tools, Proceedings of the Institution of Mechanical Engineers – Part D: *Journal of Automobile Engineering*, *235* (2021), 7, pp. 1783-1807
[13] Afzal, A., *et al*., Thermal Management of Modern Electric Vehicle Battery Systems (MEVBS), *Journal of Thermal Analysis and Calorimetry*, *144* (2021), 4, pp. 1271-1285
[14] Amini, M. R., *et al*., Hierarchical MPC for Robust Eco-Cooling of Connected and Automated Vehicles and Its Application Electric Vehicle Battery Thermal Management, *IEEE Transactions on Control Systems Technology*, *29* (2020), 1, pp. 16-328
[15] Rana, T., Yamamoto, Y., Universal Electric Vehicle Thermal Management System, *SAE International Journal of Advances and Current Practices in Mobility*, *3* (2020), 2, pp. 604-613

Paper submitted: August 25, 2022
Paper revised: October 26, 202
Paper accepted: November 6, 2022