# $LiFePO_4$ Optimal Operation Temperature Range Analysis for EV/HEV

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**Abstract.** The LiFePO4 batteries are widely used in Electric Vehicle(EV)/Hybrid Electric Vehicle(HEV) because of the high energy and power density. However, high environment temperature could accelerate the aging of batteries, while low temperature could reduce output power capability. Therefore, optimal working temperature for batteries should be determined to maintain good performance in all kinds of tough conditions. In this paper, the optimal working temperature range for batteries is analyzed. The capacity loss model is applied to determine the upper limit. The lower limit is calculated taking available capacity and output power loss into consideration. Simulation and experimental results show that the working temperature range between 10℃ and 40℃ could ensure the performance and available capacity.

**Keywords:** Electric Vehicle, Hybrid Electric Vehicle, $LiFePO_4$, optimal working temperature.

## 1 Introduction

With the problems of energy crisis and environment becoming increasingly prominent, Electric Vehicles(EVs)/Hybrid Electric Vehicles(HEVs) have attracted more and more attention[1]. Lithium-ion batteries are becoming the best choice for solving these problems owing to the characteristics of high energy and power density[2]. But the drawbacks such as cost, safety and lifetime are the bottlenecks for EVs/HEVs taking the place of traditional vehicles. The performance of power $LiFePO_4$ tends to be greatly affected by temperature, high temperature may accelerated aging and lead to thermal run away[3]. It is reported that he slow charge transfer at the electrode/electrolyte interface leads to the poor performance at low temperature[2]. At extreme low temperature the cell capacity fades greatly comparing to the nominal capacity under room temperature [4]. Wide range working temperature has great influence on the performance and safety for EVs/HEVs. The traditional fuel vehicles have been developed over 200 years and have been able to withstand the harsh environment, while the EVs/HEVs must solve the problem of battery pack thermal management to get satisfied performance at an extreme cold or hot temperature. The optimal operation temperature range is available to provide references for TMS and to prevent undesirable performance fade caused by environment.

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The goal of battery thermal management is to maintain the battery within optimal temperature range. For example, the aging and resistance rise caused by high temperature and the available capacity and power fade caused by low temperature[5]. The battery thermal management methods mentioned in the literatures include: the forced air cooling[6], liquid-based thermal management system [7,8],PCM based thermal management system [9,10] and Thermo Electric Cooler(TEC) based heating/cooling. [11,12] The forced air cooling is the traditional method for cooling, the air flows across the surface of battery pack to take the heat away, this method has been used in the Toyota Prius HEV application[13]. The liquid-based thermal management takes the heat away directly or indirectly by liquid such as water, glycol, oil, acetone or even refrigerants. Thanh-Ha Tran designed a flat heat pipe cooling system, which could reduce the thermal resistance by 30% comparing with the natural air cooling[7]. Zhonghao Rao[14] developed a thermal management system whose maximum temperature could be controlled below 50℃ when the heat generation rate was lower than 50 W and the maximum temperature difference is below 5℃. The phase change materials(PCM) are developed rapidly recent years, PCM absorb heat released by battery and make the temperature decrease rapidly, the heat is stored in the form of PCM. The heat releases to the battery when in extreme cold environment. The blower and pump are no longer needed in the PCM system. Selman and Al-Hallaj did some research on the PCM and take the PCM to battery thermal management system for the first time. In [15],they established 2D model for comparing four thermal methods: (1) natural convection cooling; (2) presence of aluminum foam heat transfer matrix;(3) use of phase change material (PCM); and (4) combination of aluminum foam and PCM. They came to the conclusion that the use of aluminum foam with PCM causes a significant temperature drop of about 50% compared to the first case of no thermal management. In [16] the PCM and air-based methods are compared and the advantages of heat pipe under extreme cold temperature were highlighted. Chakib Alaoui worked on the TEC heater/cooler based on Peltier effect for several years. The TEC based heater/cooler controls the temperature of cabin and battery pack and took the place of vehicle air conditioning [12]. In [11], the TEC was placed on the surface of each cell for the 24 series connected battery pack. The Coefficient of Performance (COP) under the condition of US06 was as high as 1.2 and the energy consumption is only 4% of the fully charged pack.

Although there were many methods for battery thermal management, the temperature control target is not uniform. Ref[17] argues that the highest battery operating temperature should below 40℃ and the maximum temperature differences is within 5℃. The FreedomCAR Battery Test Manual [18] defines the working temperature range to be between -30℃ and 52℃. The wide range of working temperature could not ensure the performance of battery pack. Thus, there should be a specific optimal working temperature range for battery pack considering the power and capacity characterizes.

In this paper, the experiments are taken first to test the temperature characterizes of battery. Then the results of HPPC and cold cranking tests are analyzed. The cell capacity loss model is used to analyze the aging of battery under high temperature the power fade is analyzed according to capacity loss and power capability. Finally, the optimal operation temperature range is determined.

## 2 Experiment Design

### 2.1 Measurement Equipment

The commercial $LiFePO_4$ used in the temperature characteristic experiment is 5Ah/3.2V (Voltage range 2.5V-3.65V). The test platform contains Arbin BT2000 battery tester(Output current range 0-100A, Voltage range 0-18V, Accuracy 0.02%-0.05%FSR) and Testsky temperature control box (Temperature range -40℃-200℃, Accuracy ±0.5℃). Fig.1 shows the devices for experiment.

**Fig. 1.** The devices for battery test and temperature control

### 2.2 HPPC Tests at Different Temperatures

The cell samples are placed in different temperature environments (-20℃,-10℃, 0℃, 10℃, 20℃, 30℃, 40℃, 50℃, 60℃) for 5 hours respectively. Each cell was fully charged by constant current and constant voltage (CCCV) under different temperature. The charge current was 9.37A and the discharge current was 12.5A . The HPPC test was taken every 10% SOC intervals with 1C rate discharge current. The HPPC test profile is shown in Fig. 2. In Fig. 2 the dotted line represents the current, the solid line represents the voltage. The experiment is stopped as soon as the call voltage reaching the cutoff voltage.

### 2.3 Cold Cranking Tests

According to the FreedomCAR Battery Test Manual [18], the pack should be replaced when capacity fades to 80% of the rated capacity. In order to further study the output power performance, a power pulse start test is taken according to the FreedomCAR Battery Test Manual [18]. The pulse profile is shown in Fig.3.The tests are conducted under different SOCs and temperatures, the maximum output power is measured every 10% SOC internals. The steps are as follows:

1) Charge the cell to fully charged (Constant current and then constant voltage)
2) Discharge to the target SOC
3) Rest for 5 hours under the target temperature

4) Take 3 power pulse tests at constant power, each pulse lasts 2 seconds and rest for 10 seconds. As is shown in Fig.7
5) If the discharge cutoff voltage is met, return to step1) and decrease the power value in step 4)
6) If the steps are finish, repeat step1 and increase the power value in step 4) until the maximum power is found.

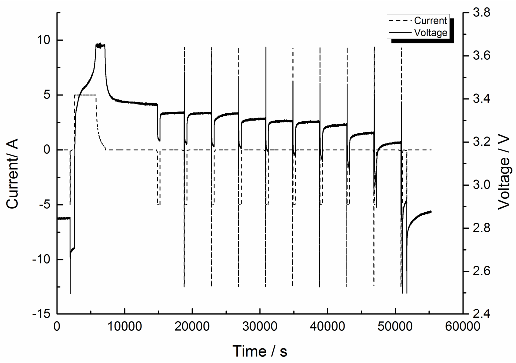


**Fig. 2.** The HPPC test profile

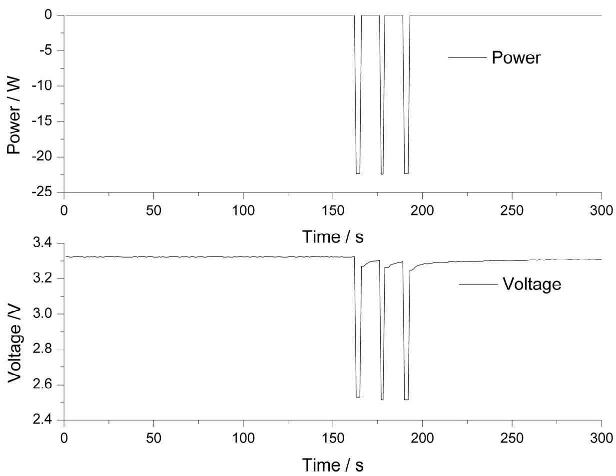


**Fig. 3.** The constant power start pulse profile

## 2.4 Results and Discussion

The results of the HPPC tests at different temperatures are shown in Fig.4-Fig.6 and that for cold cranking are shown in Fig.6.

Fig.4 shows that the discharge capacity of the same cell under different temperature conditions. It could be seen that the cell capacities are nearly the same at the temperature between 40℃ and 60℃, while the cell capacity decreases obviously with the decrease of temperature, especially below 0℃. The cell capacity is 80% at 0℃ and could hardly discharge at -20℃.

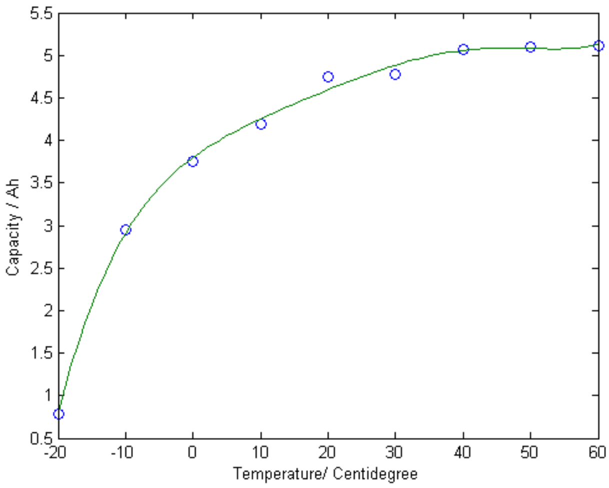


**Fig. 4.** The cell capacity profile at different temperatures

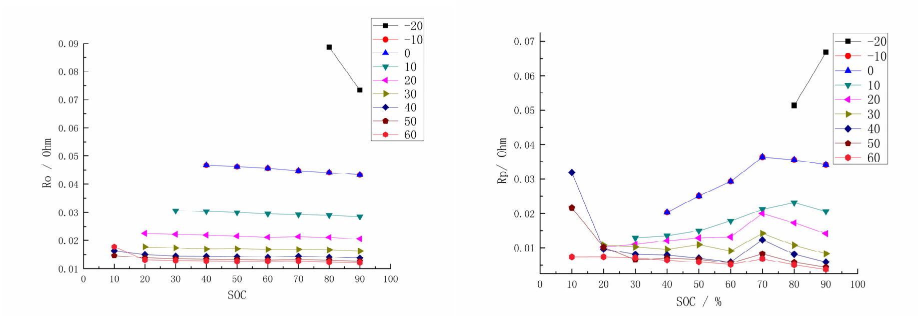


**Fig. 5.** The cell ohmic resistance and polarization resistance at different temperatures and SOCs

The discharge capacity fades with the decrease of temperature. The ohmic resistance and polarization resistance (Ro and Rp) under different temperatures are indentified according to the method mentioned in FreedomCAR Battery Test Manual [18]. Just as shown in Fig.4. The ohmic resistance changes a little at different SOCs at the same temperature. The ohmic resistance increases with the drop of temperature. The polarization resistance decreases with the drop of temperature, but it changes greatly at different SOC under the same temperature. Due to the discharge capacity is almost zero, the data at -20℃ is not universal.

Fig.6 shows the maximum charging and discharging power at different temperatures and SOCs. The maximum charging and discharging power at target SOC is defined as the product of maximum charging/discharging voltage during pulse and the current. The charging power increases with the drop of temperature, while the discharging power fades with the decrease of temperature. At the same temperature the charging and discharging power in the full SOC range are nearly the same.

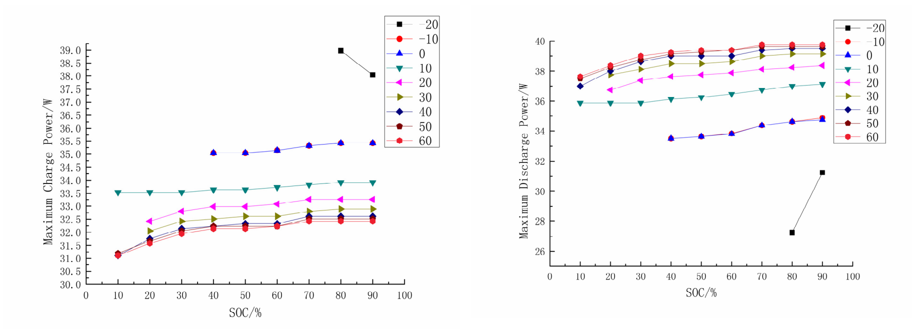


**Fig. 6.** The maximum charge and discharge power at different temperatures and SOCs

## 3 The Optimal Operation Temperature Range

As is analyzed in Section 2.3, the target cell capacities at a temperatures higher than 40℃ are nearly the same, while the discharge capacities begin to fade below 0℃. Many researches claim that high temperature accelerates the aging[19] and the performance fades during low temperature [20].In this section, the operation temperature range is determined considering the current output power capability and long term lifetime.

### 3.1 The Determination of Operation Temperature Range Upper Limit

John Wang established the capacity loss model taking DOD, temperature, discharge rate into consideration in his research[19].

$$Q_{loss} = B \cdot \exp(\frac{-31700 + 370.3 \times C_{rate}}{RT})(A_h)^{0.55} \tag{1}$$

Where $Q_{loss}$ is the percentage of capacity loss, B represents the pre-exponential factor, $A_h$ the Ah-throughput, which is expressed as Ah = (cycle number)×(DOD)×(full cell capacity), and z is the power law factor, R is the gas constant. T is the absolute temperature.

Yuejiu Zheng[21] further developed the model and have confirmed the parameter B.

$$B = 10000(\frac{15}{C_{rate}})^{1/3} \tag{2}$$

The 1C rate discharge capacity loss is calculated according to equals (1) and (2)

$$Q_{loss} = 24662 \cdot \exp(\frac{-31329.7}{RT})(A_h)^{0.55} \tag{3}$$

The aging experiment takes considerable time and work. To explain the temperature influence on aging, we take the 1C discharge rate with 80% DOD capacity loss model to simulate and analyze. The simulations under the conditions of 10℃ to 60℃ (10℃ internals) are taken. The results are plotted every 50 points, as is shown in Fig.7.

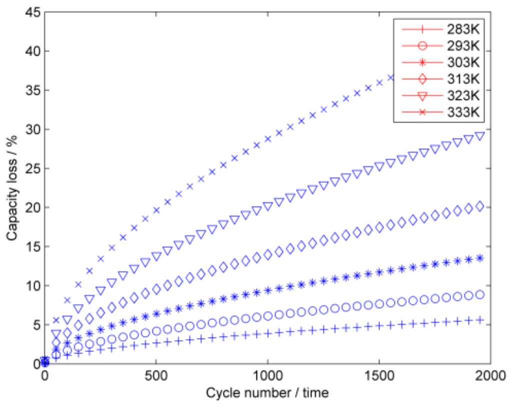


**Fig. 7.** The capacity loss simulation at different temperatures

When the cycle number comes up to 2000, the capacity losses below 40□ are lower than 20%. The 2000 times cycle is enough for the lifetime of both the battery and vehicle. Additionally, the maximum average temperature in summer is 40□, the maximum capability for thermal management system is to make the temperatures in and out of the EV/HEV nearly the same. To sum up, 40□ is determined to be the upper limit of operation temperature range to maintain the performance and prevent accurate aging caused by high temperature.

### 3.2 The Determination of Operation Temperature Range Lower Limit

The low temperature affects the charge transfer at the electrode/electrolyte interface, which leads to the significant plating on the negative electrode during charging. It irreversibly causes the capacity loss. Low temperature affects the driving distance and output power performance for EVs/HEVs.

The maximum output power test results at different SOCs and temperatures are shown in Fig.8. It shows that at room temperature, the maximum output power is 38W with almost no change within the whole SOC range. With the decrease of temperature, the maximum output power fades gradually at the same temperature and different SOCs. For example, at -10°C and 100% SOC the maximum output power is the same as that at room temperature. However, the power differences between 10% and 100% are 10W. When the temperature comes to 10℃, the output power is similar to that of room temperature and the power differences are little with different SOC. Thus, the lower limit of operation temperature range is determined to be 10℃.

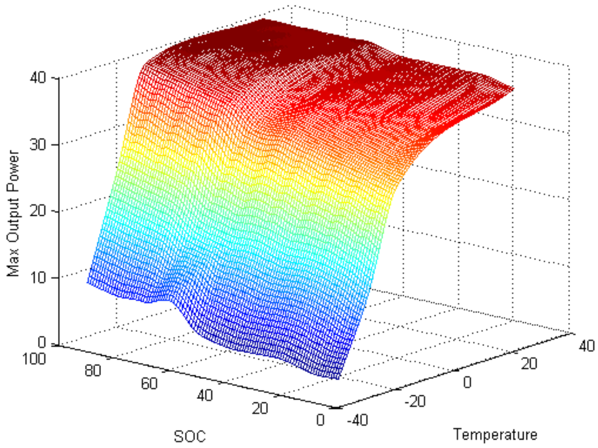


**Fig. 8.** The maximum output power at different temperature and SOC

## 4 Conclusion

In this paper, we proposed the optimal temperature operation range for batteries in EV/HEV. We first take the HPPC and cold cranking tests under different temperatures to obtain the temperature characteristics of $LiFePO_4$. And then the upper limit is determined according to the aging model. The lower limit is determined considering discharge capacity loss and output power fades. Finally, the optimal operation temperature range is proved to be 10℃ to 40℃ according to the experimental results. The range provides a temperature control target for pack thermal management. Working in the proposed temperature range is good for maintaining vehicle in good performance and reducing energy loss during heating or cooling.

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## References

1. Lu, L., Han, X., Li, J., Hua, J., Ouyang, M.: A review on the key issues for lithium-ion battery management in electric vehicles. Power Sources 226, 272–288 (2013)
2. Bandhauer, T.M., Garimella, S., Fuller, T.F.: A Critical Review of Thermal Issues in Lithium-Ion Batteries. Electrochem Soc. 158(3), R1–25 (2011)
3. Zhang, X.: Thermal analysis of a cylindrical lithium-ion battery. Electrochim Acta 56(3), 1246–1255 (2011)
4. Tippmann, S., Walper, D., Balboa, L., Spier, B., Bessler, W.G.: Low-temperature charging of lithium-ion cells part I: Electrochemical modeling and experimental investigation of degradation behavior. Power Sources 252(0), 305–316 (2014)
5. Rao, Z.H., Wang, S.F.: A review of power battery thermal energy management. Renewable & Sustainable Energy Reviews 15(9), 4554–4571 (2011)
6. Yang, Y., Hu, X., Qing, D., Chen, F.: Arrhenius Equation-Based Cell-Health Assessment: Application to Thermal Energy Management Design of a HEV NiMH Battery Pack. Energies 6(5), 2709–2725 (2013)
7. Tran, T., Harmand, S., Desmet, B., Filangi, S.: Experimental investigation on the feasibility of heat pipe cooling for HEV/EV lithium-ion battery. Appl. Therm. Eng. 63(2), 551–558 (2014)
8. Park, Y., Jun, S., Kim, S., Lee, D.: Design optimization of a loop heat pipe to cool a lithium ion battery onboard a military aircraft. Journal of Mechanical Science and Technology 24(2), 609–618 (2010)
9. Fleming, E., Wen, S., Shi, L., Da Silva, A.K.: Thermodynamic model of a thermal storage air conditioning system with dynamic behavior. Appl Energ. 112(SI), 160–169 (2013)
10. Zhang, X., Kong, X., Li, G., Li, J.: Thermodynamic assessment of active cooling/heating methods for lithium-ion batteries of electric vehicles in extreme conditions. Energy 64, 1092–1111 (2014)
11. Alaoui, C.: Solid-State Thermal Management for Lithium-Ion EV Batteries. IEEE T. Veh. Technol. 62(1), 98–107 (2013)
12. Alaoui, C., Salameh, Z.M.: A novel thermal management for electric and hybrid vehicles. IEEE T. Veh. Technol. 54(2), 468–476 (2005)
13. Zolot, M., Pesaran, A.A., Mihalic, M.: Thermal evaluation of Toyota prius battery pack. In: 2002 Future Car Congress, Arlington, VA, United states (2002)
14. Rao, Z., Wang, S., Wu, M., Lin, Z., Li, F.: Experimental investigation on thermal management of electric vehicle battery with heat pipe. Energ. Convers Manage. 65, 92–97 (2013)
15. Khateeb, S.A., Amiruddin, S., Farid, M., Selman, J.R., Al-Hallaj, S.: Thermal management of Li-ion battery with phase change material for electric scooters: experimental validation. Power Sources 142(1-2), 345–353 (2005)
16. Kizilel, R., Sabbah, R., Selman, J.R., Al-Hallaj, S.: An alternative cooling system to enhance the safety of Li-ion battery packs. Power Sources 194(2), 1105–1112 (2009)
17. Park, C., Kaviany, M.: Evaporation-combustion affected by in-cylinder, reciprocating porous regenerator. Journal of Heat Transfer 124(1), 184–194 (2002)
18. ID, D. FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles (2003)
19. Wang, J., Liu, P., Hicks-Garner, J., Sherman, E., Soukiazian, S., Verbrugge, M., et al.: Cycle-life model for graphite-LiFePO4 cells. Power Sources 196(8), 3942–3948 (2011)

20. Yi, J., Kim, U.S., Shin, C.B., Han, T., Park, S.: Modeling the temperature dependence of the discharge behavior of a lithium-ion battery in low environmental temperature. Power Sources 244(SI), 143–148 (2013)
21. Zheng, Y., Ouyang, M., Lu, L., Li, J., Han, X., Xu, L.: On-line equalization for lithium-ion battery packs based on charging cell voltages: Part 1. Equalization based on remaining charging capacity estimation. Power Sources 247, 676–686 (2014)