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Theoretical Study on Thermal Management of Lithium-ion Battery Pack with Chiller Plates and Glycol

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Abstract

The preferred candidate for Electric Vehicles is the lithium-ion battery due to its outstanding characteristics such as high energy-to-weight ratio, high voltage, good stability, and slow loss of charge when not in use. With all these advantages, fast charging and thermal management of lithium-ion battery packs are typical problems. Temperature rise in the hybrid and electric vehicle battery pack is directly proportional to the magnitude of charge/discharge power and driver demand. This theoretical study pays attention to the liquid cooling of the battery pack with chiller plates concerning higher ambient conditions to reduce the high-temperature excursions. Coolant flows through chiller plates and helps in carrying away the heat from the pack. Two types of coolant, 50% propylene with 50% water and 50% ethylene with 50% water mixture by volume are used in this study. The study reveals that with a 50-50 propylene glycol and water mixture pack temperature is reduced from 30 to 20 °C in 100 seconds while with a 50-50 ethylene and water mixture pack temperature is reduced from 30 to 20 °C in 320 seconds. The study is carried out with MATLAB/Simulink using an equivalent circuit model with two RC pairs.

Keywords: Battery Thermal Management, Liquid Cooling, Lithium Ion battery,Equivalent circuit model , MATLAB/ Simulink and Glycol

1.0 Introduction

One of the problems that our world faces today is climate change due to increasing CO_2 emissions and pollutants generated from industries and vehicles. The transportation industry was responsible for 24% of the direct carbon dioxide (CO_2) emissions from fuel combustion in 2019[1]. A possible solution is the usage of electric vehicles (EVs) as an alternative to reduce some parts of the air pollution problem through original equipment manufacturers (OEMs) [2]. These electric vehicles require a suitable electric storage system which provides a long driving range and desirable acceleration capability which needs large-scale capacity and high operating voltage [3]. Among other existing power batteries, lithium-ion batteries, which have low self-discharge rates, high energy density, good stability and high voltage, are supposed to be the most attractive and desirable energy storage solution in EV, HEV and PHEV applications [4][5]. However there is variation in cell capacity, voltage and internal resistance [6] and as a result, when cells undergo charging /discharging it creates uneven temperature[7][8] Furthermore, short circuits or internal defects within individual cells and heat dissipation at the centre and edge of the module may result in 'hotspots' within the module/pack, leading to thermal runaway and catastrophic failure [9] Such a scenario could escalate to severe failures at the module/pack level and ultimately to vehicle fires if no appropriate means are adopted to prevent the propagation of Thermal runaway. The performance and safety of the LIB battery module fully depend on battery temperature, Experiments and numerical thermal simulation methods are used to measure the battery temperature. However experimental approach has it is own limitations in measuring inside battery temperature with a sealed container, one setup can measure specific conditions only and is time-consuming.

To achieve the optimum performance of the battery module, a Lithium-ion battery needs to operate between 20 to 40℃ [10]. For achieving optimum performance, BTMS needs to maintain a maximum operating temperature of the lithium battery of less than 60℃ (inside the battery), a maximum temperature difference between the cell less than 5°C and a temperature difference between modules less than 10℃ [11]. Nowadays, significant research work has been spent and the development of advanced battery thermal management systems is available for achieving battery temperature targets. BTMS can be divided into air cooling, liquid cooling, PCM and heat pipes according to cooling medium and method [12]. Air cooling systems are very simple, easy to integrate and operate, lightweight weight and low cost every air has lower specific heat and lower thermal conductivity properties therefore it is very difficult to maintain uniform temperature of battery module at higher ambient and higher battery loading conditions [13] [14]. Phase change material cooling system is another cooling strategy which is more familiar due to the high latent heat of PCM materials, it can absorb battery heat by changing phase and maintaining uniform temperature at extreme operating conditions, compared to air and liquid cooling PCM is very simple because PCM not having component's like pump, motor, ducts, plumbing and fans etc. It is lighter and has lesser operating and maintenance costs. Due to its lower thermal conductivity, which leads to poor performance in the battery pack, it is not a preferred mode of cooling [15] [16]. Heat pipe cooling systems are effective cooling systems due to their simple structure, lightweight and no external power is required to operate the system. However, heat pipes have limitations concerning operating environment such as inclination, vibration etc and working fluid [17] [18].

Compared to other cooling systems liquid cooling systems are the most effective cooling system strategy due to their higher specific heat and higher thermal conductivity. Moreover, liquid cooling systems occupy a lesser volume to achieve the same performance targets [19]. Liquid cooling systems are already implemented in the majority of OEMs like Model S in Tesla, Chevrolet VOLT Chevrolet Spark in General Motors and Focus BEV model from Ford, where the cooling system meets BTMS targets [20]. In the liquid cooling system, water /glycol mixers and Di-electric liquids such as silicon oil, mineral oil, deionized water, nanofluid and Hydro Fluro Ether are used. Di-electric mineral oils are more attractive due to their electrically nonconductive properties. It provides better heat transfer than a water/glycol mixer due to direct contact with the battery system. However, its pressure drops are very high due to the higher viscosity of oil which leads to higher power consumption of oil pumps. A water/glycol mixer is used as a cooling medium which has a lower viscosity than most of the oils, resulting in a better heat transfer coefficient and it passes through discrete tubes or placing modules on cold sink plates or jackets containing cooling liquid to conduct heat from cell [21] [22].

In this work water /glycol coolant mixer is selected as a liquid cooling medium for further enhancing BTMS performance. Two different liquids Ethylene glycol and Propylene glycol are used to evaluate the potential benefit of battery thermal management. To reduce the time, cost and complexity of testing, a theoretical approach is adopted in this work to test the BTMS of the battery pack. To do this, an equivalent circuit model with two RC pairs is used to develop a battery pack in which 20 cells are connected in series. Using MATLAB - Simscape the developed model is validated to reduce the maximum temperature of the battery pack and make it work under the optimum temperature range

2. Modelling and Simulation

2.1 Equivalent Circuit Model

A lithium-ion cell is modelled using Simscape by implementing the elements of an equivalent circuit with two RC branches. Each element of the equivalent circuit is a function of SOC and temperature. Values of R_0, R_1, C_1, R_2, and C_2 are taken from the experiment results and incorporated in the form of lookup tables for different SOC and temperature values. Temperature and Current (Amps) are the inputs given to this model. The pulse discharge test characterizes the battery voltage response (cell dynamics) at various SOCs and temperatures.

This simulation comprises a series of discharge pulses across the full SOC range under specified temperature points with a pulse current of 0.8C rate (2A) with 450 seconds discharge time and 45 min relaxation period. By using these values and inputs, a simulation is carried out to calculate the heat generated by each cell and the

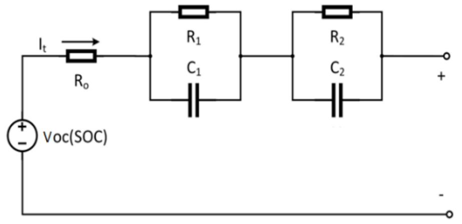

Fig 1 Equivalent circuit model.

entire battery pack. The equivalent circuit with 2 RC pair is shown in Fig.1 and Fig.2 shows the battery model developed in Simscape.

2.2. Battery Pack Model

A single 2-RC equivalent circuit model (as shown in Fig.1) is connected in series to build a single battery pack. Each battery pack consists of 20 cells which are connected in series. In this way, 4 battery packs were made and these all are also connected in series. Inside each pack, a thermal model is also developed and all these 20 cells are connected to this model which helps to measure the temperature of the whole pack. To develop a cooling system for an electric vehicle in real real-time scenario FTP-75 Driving cycle is chosen as input to this system. Current is provided as input to the battery packs and speed from the driving cycle is taken as input to the cooling system. The battery module is shown in Fig 2.

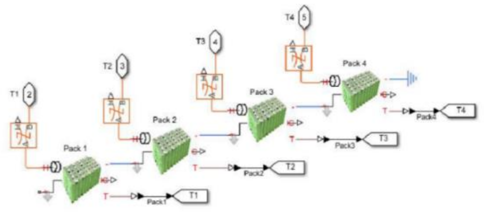

Fig .2 Battery pack model

2.3 Liquid Cooling System

For liquid cooling, a refrigerant system and radiator are used as a cooling unit as shown in Fig 5. In this system liquid is the main element So, the storage tank is used to store the liquid and liquid flows refrigerant system and radiator through a fluid pipe. A mass flow rate sensor is connected to the pipe and this is used to measure the flow rate and temperature of the refrigerant. This liquid is also passed to the radiator to cool the liquid. Liquid from both systems are combined and sent to the constant volume chamber. A controller is used to control the temperature of the liquid inside the chamber and the liquid is passed only if the temperature is under the given conditions.

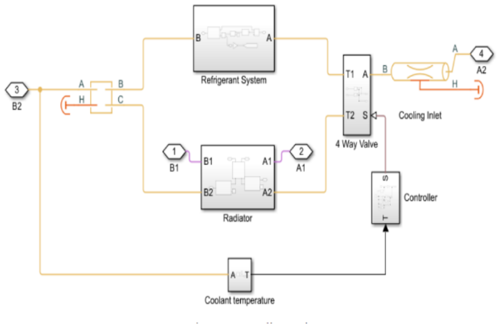

Fig 5. Cooling unit

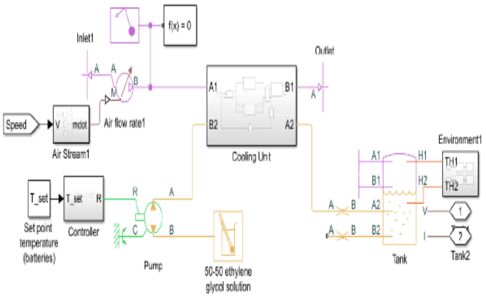

Fig 6. Liquid cooling system

Once the liquid temperature is set, the outlet of the cooling system is connected to the pump and then to the liquid medium. A controller is used to control the working of the pump based on the set temperature. So, when the set temperature is reached by the battery the pump stops working. The liquids that are used here are water and 50-50 ethylene glycol and water as shown in Fig 6. To cool the battery packs cold plates were used. So, the liquid is taken as an inlet to these cold plates through a fluid pipe. The heat source from the battery is placed in between the conductive channels of the battery and the plate mass. By using a conductive cooling channel, the heat from the cold plate is transferred to the liquid as shown in Fig 7. temperatures between the battery packs or to show the decrease in the maximum temperature of the batteries. To simulate for uniform temperature of the pack the fluid pipes should be connected in parallel shown in Fig 8.

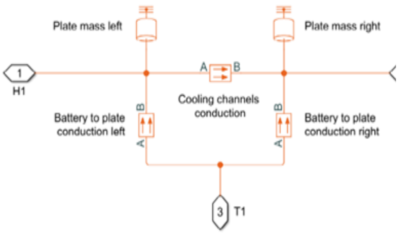

Fig 7 Cold plates

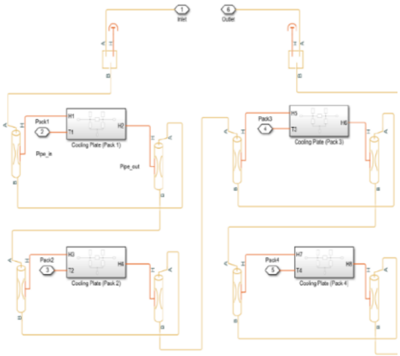

Fig 8 Arrangement of cold plates

3.0 Results and Discussion

3.1 Validation Results

A single RC equivalent circuit is modelled in MATLAB/Simulink and a pulse current is given as an input. The terminal voltage output of the equivalent circuit is shown in Fig 9. As the current input that is given is a discharge current, the terminal voltage gets decreased from 3.6V to 3.25V. During discharging, there is an instantaneous decrease in voltage without any change in time which is due to current (i) and internal resistance (R0). But later we observe the voltage response is non-instantaneous to the change in current input this is due to the resistance and capacitor pair. Again, the voltage increases from terminal voltage to open circuit voltage during the relaxation period. Slow relaxation of voltage is caused by slow internal diffusion of lithium from one part of the battery cell to the other where concentration gradient builds up while the cell is being discharged and they slowly relax back to their equilibrium values.

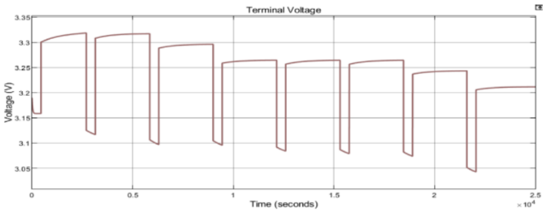

Fig 9 Validation of terminal voltage

3.2 Battery Pack

3.2.1 Voltage

The discharge current shown in Fig 3 is input to the battery pack model. The voltage at 100% SOC is around 328 V. As the current fluctuates the voltage also fluctuates as shown in Fig 10. When the discharge current reaches a peak value, the voltage decreases. This happens because when more current flows through an internal resistance, the voltage drop along the internal resistance is high. So, the terminal voltage will be the difference between open circuit 36 voltage and the voltage drop (i.e., product of internal resistance and current). After running the model for 1400 seconds the voltage reaches a value of 302.5V.

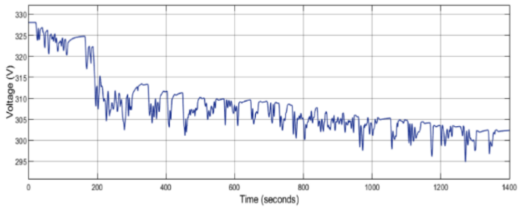

Figure 10. Battery pack volt

3.2.2 State of Charge (SOC)

The state of charge is the amount of available energy present inside the battery. Initially, the SOC was 92 %. During the process of discharging, the SOC value decreases as the voltage of the battery pack decreases. The state of charge detail is shown in Fig 11. After 1400 seconds of simulation, the SOC reaches a value of 50 %.

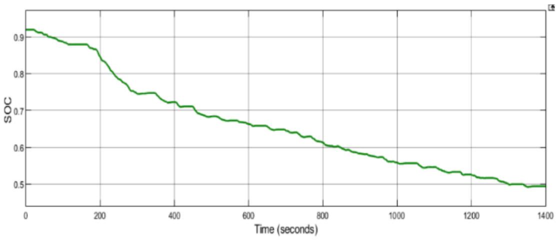

Fig 11 State of the charge battery pack

3.2.3 Temperature

The temperature of the battery pack starts increasing from its initial temperature of 30 °C and reaches to maximum temperature of around 55°C by the end of the simulation as shown in Fig 12. The reason is that there is no cooling medium provided to the battery pack. As there is no cooling medium, heat transfer will not take place from the battery pack.

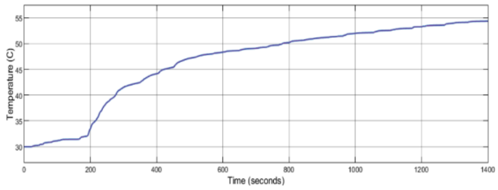

Figure 12. Temperature of battery pack without any cooling

3.3 Liquid Cooling

3.3.1 50-50 Ethylene glycol and water mixture:

The cooling medium that is used here is a mixture of 50 % ethylene glycol (EG) and 50 % water. When the temperature source from the battery pack is given to the liquid which flows inside the cold plates, takes away the heat. Fig 13 Shows Temperature Behaviour using EG and water mixture. Initially, the heat transfer from the source takes place to the cold plate and from there the heat transfers to the liquid medium, therefore cooling the battery pack. The temperature starts reducing from the initial temperature of 30 °C and goes to 20.5°C within 380 seconds. After reaching 20.5°C, which is a set temperature given to control the operation of the pump the temperature of the battery pack starts to increase slightly till the end of the simulation.

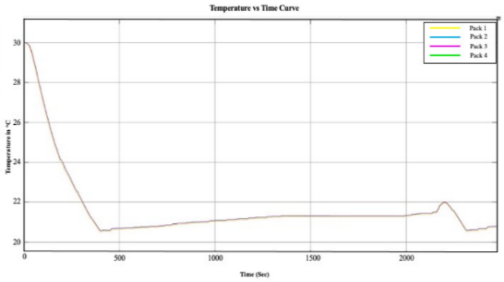

Fig 13 Battey temperature using EG/water mixture

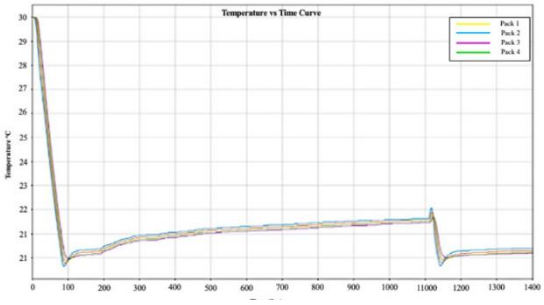

Fig 14. Battery temperature using PG/water mixture

3.3.2 50-50 Propylene glycol and water mixture:

When 50% propylene glycol (PG) and 50% water mixture is used as a liquid medium, the temperature of the battery pack reduces from 30°C to around 19.8°C in less than 100 seconds compared to 50-50 Ethylene glycol and water mixture which took around 380 seconds. Fig 14 Shows Temperature Behaviour using a PG and water mixture. In this case, the battery pack temperature gets reduced faster because the specific heat of propylene glycol is higher compared to ethylene glycol. As the pump stops working after reaching the set temperature, the temperature of the battery pack starts rising slightly. Around 1120 seconds, again the pump starts to operate allowing the liquid to flow to the cold plate. So, the temperature of the pack again drops down and continues to increase slightly till the end of the simulation

3.3.3 Coolant and Refrigerant Pumping Power

The liquid from the tank flows to the cold plate with the help of a pump. So, when the simulation starts, the liquid starts flowing towards the cold plates and the pump power tends to increase. The pumping power details as shown in Fig 15. Initially, we can see that the pump power increases and becomes stable after some time because of the temperature gradient. A controller is used to control the operation of the pump. When the temperature of the battery pack reaches the set temperature (i.e. 20.5℃) which is given to the controller, the pump stops working and power becomes zero.

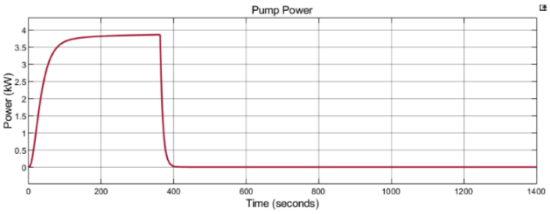

Fig 15 Pump power

Similar to pump power, refrigerant power also increases at the initial state and when the temperature gradient starts reducing, the refrigerant power also reduces. The refrigerant pumping power concerning time details are shown in Fig 16 Finally, when the pump stops working after 380 seconds, there will be no flow of liquid through the refrigerant system. Therefore, refrigerant power drops suddenly and becomes zero.

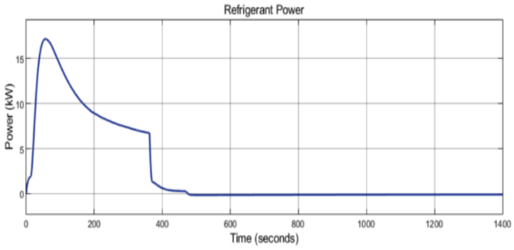

Figure 16. Refrigerant power

Conclusions

In this study equivalent circuit model with two RC pairs which represents a lithium-ion battery model is validated with the results in the reference paper and is used to develop a battery pack in which 20 cells are connected in series. Simulation results show that the temperature tends to increase around 55℃ without providing any cooling system to the battery pack. So, thermal management is implemented to reduce the temperature of the pack. Different liquids that are used in this work are 50-50 Ethylene glycol water mixture and 50-50 Propylene glycol water mixture. When 50-50 Ethylene glycol water mixture is used as a cooling medium, it takes around 380 seconds to cool the battery pack from the initial temperature of 30 to 20.5℃. When 50-50 Propylene glycol water mixture is used as a cooling medium the pack cooled down from 30 to 19.8℃ within 100 seconds which is faster compared to the 50-50 Ethylene glycol and water mixture. So, 50% propylene glycol and 50% water mixture is chosen as best cooling medium.

References

[1] Energy technolgy perspectives in 2020 International Energy Agency www.iea.org/reports/energy-technology-perspectives-2020

[2] Enrico Ferrero , Stefano Alessandrini , Alessia Balanzino Impact of the electric vehicles on the air pollution from a highway Applied Energy 169 (2016) 450–459 https://doi.org/10.1016/j.apenergy.2016.01.098

[3] John B. Goodenough ,Energy storage materials: A perspective EnergyStorageMaterials 1(2015)158–16

[4] https://doi.org/10.1016/j.ensm.2015.07.001

[5] John B. Goodenough and Youngsik Kim Challenges for Rechargeable Li Batteries Chemistry of material review Vol. 22, No. 3, 2010 DOI:10.1021/cm901452z

[6] John Warner The Handbook of Lithium-Ion Battery Pack Design Chemistry, Components, Types and Terminology XALT Energy, Midland, MI, USA

[7] L. Lu, X. Han, J. Li, J. Hua, and M. Ouyang, “A review on the key issues for lithium-ion battery management in electric vehicles,” J. Power Sources, vol. 226, pp. 272–288, 2013.

[8] doi: 10.1016/j.jpowsour.2012.10.060.

[9] U. Iraola, I. Aizpuru, L. Gorrotxategi, J. M. C. Segade, A. E. Larrazabal, and I. Gil, “Influence of voltage balancing on the temperature distribution of a Li-ion battery module,” IEEE Trans. Energy Convers., vol. 30, no. 2, pp. 507–514, 2015, doi: 10.1109/TEC.2014.2366375.

[10] M. Hoh and J. Fuhr, “EVS24 Stavanger, Norway, May 13-16, 2009,” pp. 1–10, 2009.

[11] J. B. Robinson et al., “Non-uniform temperature distribution in Li-ion batteries during discharge - A combined thermal imaging, X-ray micro-tomography and electrochemical impedance approach,” J. Power Sources, vol. 252, pp. 51–57, 2014, doi: 10.1016/j.jpowsour.2013.11.059

[12] J. Yan, Q. Wang, K. Li, J. Sun, Numerical study on the thermal performance of a composite board in battery thermal management system, Appl. Therm. Eng. 106 (2016) 131–

140. doi.org/10.1016/j.applthermaleng.2016.05.187.

[13] H. Teng, Y. Ma, K. Yeow, and M. Thelliez, "An Analysis of a Lithium-ion Battery System with Indirect Air Cooling and Warm-Up," *SAE Int. J. Passeng. Cars - Mech. Syst.*, vol. 4, no. 3, pp.1343–1357, 2011, doi: 10.4271/2011-01-2249.

[14] S. W. Zhonghao Rao, "A Review of power battery thermal energy managment," Renew. Sustain. Energy Rev. . elesewhere, vol. 15, pp. 4554–4571, 2011. https://doi.org/10.1016/j.rser.2011.07.096

[15] X.M. Xu, R. He, Research on the heat dissipation performance of battery pack based on forced air cooling, J. Power Sour. 240 (2013) 33–41. https://doi.org/10.1016/j.jpowsour.2013.03.004

[16] D. Chen, J. Jiang, G. H. Kim, C. Yang, and A. Pesaran, "Comparison of different cooling methods for lithium ion battery cells," Appl. Therm. Eng., vol. 94, pp. 846–854, 2016,doi:10.1016/j.applthermaleng. 2015.10.015.

[17] Hussain, C.Y. Tso, C.Y.H. Chao, Experimental investigation of a passive thermal management system for high-powered lithium ion batteries using nickel foamparaffin composite, Energy 115 (2016) 209-218. https://doi.org/10.1016/j.energy.2016.08.094

[18] G. Karimi, M. Azizi, A. Babapoor, Experimental study of a cylindrical lithium ion battery thermal management using phase change material composites, J. Storage Mater. 8 (2016) 168–174 https://doi.org/10.1016/j.est.2016.08.005

[19] J. Zhao, P. Lv, Z. Rao, Experimental study on the thermal management performance of phase change material coupled with heat pipe for cylindrical power battery pack, Exp. Therm. Fluid Sci. 82 (2017) 182–188 doi.org/10.1016/j.expthermflusci.2016.11.01

[20] W. Wu, X. Yang, G. Zhang, K. Chen, S. Wang, Experimental investigation on the thermal performance of heat pipe-assisted phase change material based battery thermal management system, Energy Convers. Manage. 138 (2017) 486–492.

[21] doi.org/10.1016/j.enconman.2017.02.022

[22] H. Liu, Z. Wei, W. He, J. Zhao, Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: a review, Energy Convers.Manage. 150 (2017) 304–330.doi.org/10.1016/j.enconman.2017.08.016

[23] Yan Wang , Qing Gao, Guohua Wang, Pengyu Lu ,Mengdi Zhao, Wendi Ba . A review on research status and key technologies of battery thermal management and its enhanced safety Article in International Journal of Energy Research26(2017) 391-412 DOI: 10.1007/s11630-017-0955-2

[24] G. Kim and A. Pesaran, "Battery Thermal Management Design Modeling," vol. 1, pp. 126–133, 2007, doi.org/10.3390/wevj1010126.

[25] Yuanwang Deng, Changling Feng, Jiaqiang E,, Hao Zh, Jingwei Chen, Ming Wen, Huichun Yin, Effects of different coolants and cooling strategies on the cooling performance of the power lithium ion battery system: A review Applied Thermal Engineering 142 (2018) 10–29 doi.org/10.1016/j.est.2016.08.005