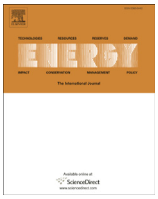
Energy 148 (2018) 247–257

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Layered thermal model with sinusoidal alternate current for cylindrical lithium-ion battery at low temperature

Jun-qiu Li*, Linlin Fang, Wentong Shi, Xin Jin

Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing Institute of Technology, Beijing, 100081, China

ARTICLE INFO

Article history:
Received 7 May 2017
Received in revised form
3 January 2018
Accepted 4 January 2018

Keywords:
Lithium-ion battery
Low temperature
Sinusoidal alternate current (SAC) heating
Layered thermal model

ABSTRACT

The poor battery discharging performance and capacity, operated at low temperature, pose a technical barrier limiting their use in electric vehicles. Therefore, the purpose of this paper is proposed to improve the performance of battery at low temperature. And a sinusoidal alternate current (SAC) heating strategy is proposed to heat the battery. The battery is heated fast and uniformly, due to a large amount of heat generated at the inside of battery when sinusoidal alternate current is transited in a battery. Meanwhile, a layered thermal model is established to simulate the heating method. The SAC heating experimental results show that a lower frequency SAC within the scope of 100 Hz can heat battery effectively. And the simulation results show that the temperature error between outer layer of simulation and experimental tested actual surface temperature is no more than 1 °C. After heated by SAC at low temperature (−20°**C**), the battery capacity is promoted 45%. The proposed heating strategy is of great potential for rapidly improving operating performance of electric vehicles in cold weather. Furthermore, the confirmed layered thermal model could be applied to the investigation of lithium-ion battery.

1. Introduction

In order to deal with global warming, environmental pollution and energy issues, the development of electric vehicle (EV) and plug-in electric vehicle (PHEV) has been encouraged by most of governments [1,2]. Meanwhile, Lithium-ion battery has been widely used in electric vehicle because of its high working-voltage, large capacity, long circle-life and environmental friendliness [3–5]. However, due to the considerable increased overall cell impedance at -20 °C or -40 °C cold temperature, the battery operated at low temperature will lead to significant reduction of discharge performance, discharge capacity and battery cycle life [6–9]. Therefore, the deteriorative performance operated at low temperature adversely restricts the feasibility and applicability of electric vehicle [10–12]. In response to this concern, recent research efforts have been devoted to preheating the battery and improve the battery performance at low temperature [12–14].

Some previous researches focus on the outer heating method, which means that heat battery by an outer heat generating device. Pesaran, A. and Vlahinos, A [15,16]. proposed external jacket heating, internal jacket heating and fluid heating strategies to warm the battery early. However, they failed to consider the loss of energy and additional heat conduction. Moreover, these strategies heat battery slowly, inefficiently and non-uniformly, even they are easy to operate. Therefore, there has been an increasing interest in the internal heating, which the heat is generated inside the battery itself [17]. As [18] shown, when the current is transited through a battery, like discharging or charging a battery, there will be considerable heat generated inside the battery. Compared with external heating, there is no extra device in the internal heating strategy, it is energy-efficient and fast [19]. And after internal heated, the battery temperature distribution is more uniform than external heating [20]. Afterwards, Zhao, X.W. et al. [21] proposed a heating battery method by high rate pulses with the charge and discharge current before the conventional charging (CC-CV) at -10 °C. However, in order to avoid lithium deposition, the amplitude and the duration of DC applied to a battery should be restricted to small values, thus it limits the heat generation rate and the preheating effectiveness [22]. In addition, the larger resistance at low temperature makes the charge and discharge process extremely difficultly, thus the charge-discharge heating strategies are difficult to be applied.

Compared to DC, the SAC can heat the battery fast effectively and uniformly, meanwhile avoiding the change of battery state of

---

* Corresponding author. No. 5 Yard, Zhong Guan Cun South Street, Haidian District, Beijing, China.

E-mail address: lijunqiu@bit.edu.cn (J.-q. Li).

https://doi.org/10.1016/j.energy.2018.01.024
0360-5442/

charge (SOC). Stuart, T.A [23]. applied a 60 Hz AC to heat some lead-acid batteries with different SOC, at cold temperatures from −20 °C to −40 °C. It found that the required heating time was easily decreased by increasing the AC amplitude. Hande, A [24]. used an inverter to generate a10-20 kHz high frequency AC to heating a pack of 16 series connected NiMH batteries. As expected, the heating process sped up as the amplitudes of the AC was increased. More recent studies by Zhang, J. et al. [22], they applied a 1C−2C rate and 0.1 Hz-10 Hz frequency SAC into a 2.8 A h rated capacity 18650 type battery at low temperature. They found that a larger amplitude and lower frequency of AC can get a better heating effect. In contrast, Ruan, H. et al. [20] believe that there is an optimal frequency of 1377 Hz. Their experiments show that the battery heating time is shortest with the SAC optimal frequency of 1377 Hz, at constant amplitude. It happens that there is a similar case in Ref. [25]. Zhu, J. et al. [25] put forward that both the sine and rectangular AC excitations obtain the maximum temperature rise at 30 Hz. Therefore, more experiments data need to be provided to find the relationship between amplitude, frequency and heating effect. Also, a heating model is needed to compute the optimal sinusoidal heating method. Some present literature have made a lot of contributions for the battery thermal model. Hallaj, S. Al. et al. [26] proposed a one-dimensional thermal mathematical model with lumped parameters to simulate temperature profiles inside lithium-ion cells. Some complex electrochemical-thermal coupled models [27–30], which contain many complicated nonlinear partial differential equations with many unknown variables, could reveal the heat generation mechanism. However, the considerable complexity not only consumes significant computation time, but also expends plentiful efforts to ensure the parameters exactly. And then, a reduced-order MSMD [31] and a pseudo two dimensional (P2D) physics-based electrochemical model [32] were proposed aimed to reduce significantly the computation load of the models. Other models based on mathematical algorithm, such as artificial neural network [33,34], are highly dependent on the trained data, and difficultly reflect the internal of battery performance.

The objectives of this investigation are aim to find an optimal SAC internal heating strategy, and develop an exactly heating model to predict the heating result. At first, numerous variable frequency and variable amplitude SAC heating experiments are conducted. These results show that a larger amplitude of SAC under the constant frequency warm battery faster, and a higher frequency of SAC under the constant amplitude need more time to achieve a set temperature. Meanwhile, a layered model combined with SAC heat generation formula is developed to simulate the heating method. The genetic algorithm is used for model parameters identification [35]. The two-layer model can predict the battery heat distribution well. The maximum mean error between outer layer and actual surface temperature result is less than 1.54 °C, which shows the two-layer model is reliable. Third, the comparisons of heated and unheated discharge experiments show that the method has a good value for the performance improvement of battery at low temperature. It should be noted that this study has little attention to the battery cycle life. Only 17 times heating experiments are conduct to investigate the impact of SAC heating strategy. After 17 times heating, the battery still have 99.69% of initial capacity, whose capacity reduction is only 0.31%. In addition, the frequency of SAC is limited within 100 Hz in the heating experiment. Because the real part of impedance changes slightly when frequency higher than 100 Hz. Therefore, according to heat generation theory, the variation of heat generation rate becomes small. Meanwhile some previous heating experiments of frequency higher than 100 Hz results show that there is little difference. All the heating experiments higher than 100 Hz have a similar heating effect, when amplitude of SAC is constant. Further studies on battery life reduction after hundreds of times SAC heating will be summarized in our next study. And the debate about the optimum frequency needs to be intensively studied.

2. Model development

When the SAC is transited through a battery, there will be a quantity of heat generated inside the battery, which can heat the battery itself. This generated heat is gradient distributed along radius direction in a cylindrical cell due to the interaction effects of internal heat generation and external heat convection under heating process. Therefore, a layered battery thermal model is suitable for the heating process simulation.

2.1. SAC heat generation rate q_{ac}

Before conduct the development of layered thermal model, the heat generation rate q_{ac} need to be checked out. Both DC and SAC can generate heat inside the battery. Different from the direct current, the applied SAC heat the battery because of the real part of battery impedance, meanwhile avoiding substantial change of SOC and the lithium deposition. Zhang, J. et al. [22] proposed a heat generation rate calculation method based on the real part of battery impedance, and this method was verified to be able to simulate the real battery heat generation. The detailed calculation steps as follows:

When the current applied upon a battery describes as this:

$$i(t) = A\sin\left(\frac{1}{f}t + \varphi\right) \tag{1}$$

The battery internal heat generation rate can be described as:

$$q_{ac} = \left(\frac{A}{\sqrt{2}}\right)^2 Z' \tag{2}$$

where Z' is the real part of battery impedance, which can be obtained by electrochemical impedance spectroscopy (EIS) [36–39]. As shown in Fig. 1, the two electrochemical impedance spectroscopy curves under different temperature are tested on an 18650 NCA/graphite cell with a 2150 mAh capacity. The abscissa axis of Fig. 1 is Z', which indicates the real part of impedance. The ordinate axis of Fig. 1 is Z'', which indicates the imaginary part of impedance. The heat generation is mainly the joule heat which correlated with

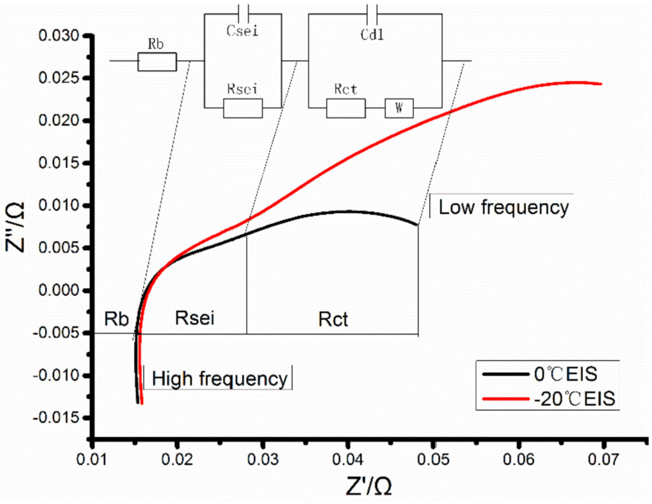


Fig. 1. The nyquist diagram of EIS under different temperature.