Review on preheating systems for lithium-ion batteries of electric vehicles under low temperature circumstance

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Abstract. Nowadays, energy and environmental protection issues have become the focus of most attention. The development of electric vehicles which depends on lithium ion battery as power source is one of the most applicable way in dealing with these issues. Lithium-ion battery (LIB) is highly favoured for its outstanding features in energy density, cycle life and energy retention. However, its severe sensitivity to working temperatures leads to problems when driving electric vehicles. Therefore, researchers and engineers have explored approaches to guaranteeing a suitable working temperature for LIB, one of which is the battery preheating system. To clarify the advancement of this system, both internal and external preheating methods studied in recent years are summarized, and the discussion for future research is included.

Keywords: preheating, lithium-ion battery, electric vehicle, low temperature

1. Introduction

In recent years, with the rapid development of science and technology and the increasing awareness of the whole society towards environmental protection and energy saving, electric vehicles have become a new trend and new direction of transportation. The development and competition of the electric vehicle industry have become increasingly fast and fierce in recent years, which becomes a vital field of competition among countries. Electric vehicles using lithium-ion batteries have great development potential and competitive advantages in this field due to the advantages of LIBs such as high energy density, long cycle life, and low self-discharge rate [1, 2]. However, at the same time, the function of lithium ions is limited by temperature to a great extent. This shortcoming leads to a decrease in the driving range, difficulty in recharging electric vehicles, and threats to driving safety at low working temperatures, which limit the design, production, and advancement of electric vehicles to a certain extent [2, 3]. Researchers have invested a lot of energy into the research and development of lithium-ion thermal management system, which can promote the realization of better battery performance, thus promoting the development of the electric vehicle industry. There are already lots of reviews on lithium batteries' thermal management system, especially the cooling system. Preheating systems for lithium ion battery have also been studied and improved in recent years, but there are relatively few review papers focused on preheating systems and discuss both the application of preheating methods for LIBs and temperature uniformity of LIBs when these methods are utilized. In this review, an explanation on LIBs for electric vehicles is given firstly and following is an illustration of the characteristics of LIBs at low temperature. Then, several preheating methods used for keeping LIBs in a suitable temperature range are introduced and the corresponding researches are reviewed. In the end, it ends up with conclusion and discussion for future research and prospect.

2. Lithium-ion battery

2.1. LIB for electric vehicles

Electric vehicles reduce the dependence on fossil energy as well as the environmentally hazardous emissions of society as a whole and contribute to mitigating the energy shortage and the global climate crisis. They can be charged by electricity produced by a power station or clean sources such as wind, solar energy, hydroelectricity, and so on. For achieving this recharge, the key point in this process is the battery technology. Depending on the advantages of high energy density, low self-discharge rate and long recycling life, the lithium-ion battery stands out from the secondary batteries and now becomes a common option for the power source of electric vehicles. LIB technology is deemed one of the most promising energy storage technologies in the 21st century. Although LIBs are widely used in the vehicle industry, the limited proper working temperature range is still a hindrance to advancement.

2.2. Low temperature performance

The performance of LIBs is highly related to the temperature. Commonly, the proper working temperature is 0-40°C. Remaining in subzero-temperature environments and working in a low-temperature environment for a long time can induce significant attenuation to the LIBs, represented by longer recharging times, decreased discharge capacity, and fast energy loss. All of these issues can lead to an undesirable driving range for electric vehicles. The study by Wang et al. [4] shows the LIB discharge capacity meets a sharp drop when put into an environment below -5 °C. Specifically speaking, at -10°C, -20°C, and -30°C, the actual discharge capacity becomes 88.0%, 82.5%, and 32.79% of the desired capacity at room temperature, respectively. From a theoretical point of view, under low-temperature circumstances, there is a decline in the chemical reaction rate and electrolyte conductivity of batteries, which causes difficulty in the transportation of lithium ions On the macro level, the internal resistance of the battery increases to a large extent. In addition to these problems, the electrode suffers lithium deposit which causes loss of active material. In a more dangerous situation, lithium dendrites appear and tend to cause a short circuit inside the lithium-ion battery, increasing the risk of battery damage and even explosion [3][5],[6]. Thus, it is necessary to install preheating device into the thermal management system of lithium batteries on electric vehicles to guarantee the LIBs functioning in a proper temperature when the EVs start and to improve both the effectiveness and safety.

2.3. Applying preheating system

Battery preheating is conventionally categorized into two types: the internal preheating and external preheating. AC heating, DC heating and pulse self-heating are included in internal heating. Through internal heating, the batteries are preheated primarily by self-generated heat or the heating device installed in the batteries. Internal preheating is deeply researched and promoted due to the advantages of high preheating speed, excellent energy efficiency and good ability in temperature uniformity realization. However, the technology requirement of internal preheating is relatively higher than external preheating and contains some latent safety issues. External preheating mainly relies on the external heat source and need heat transfer to assist conducting heat to the battery pack. The methods mainly include air heating, liquid heating, and phase-change material heating. Compared to internal preheating, it is cheaper, safer, and easier to apply, but it is not competent for achieving good temperature uniformity [5]. In the next two sections, research on these commonly used preheating methods is reviewed.

3. Internal preheating

In the traditional way of lithium battery preheating, the heating current remains to constant. Generally, a large AC current can accelerate the preheating process but can potentially bring much more damage

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to battery at the same time. A small AC current used to preheat the battery will be safe but takes more time to achieve the ideal working temperature. Meanwhile, when battery is heated to a relatively high temperature, it can tolerate a higher AC heating current without receiving damage. Therefore, it is of importance to find a solution to balance the preheating speed and the potential damage to the battery. Based on this idea, Shang et al. [7] builds an internal preheating model called high-gain control based preheating model which can automatically change the preheating current according to the real-time battery temperature to realize the balance of temperature rising and battery safety. The results of their experiments show that, compared to the conventional internal preheating model, the proposed model succeeds in preheating the battery in a limited time and applying the maximal safe heating current dynamically through the whole process of preheating. The advantage of this model is particularly obvious when functioning under extremely freezing circumstances.

Du et al. [8] establish a preheating model using a closed-loop control (CLC) strategy on the basis of pulse heating theory. This model aims to regulate the temperature uniformity during the preheating process. The experiment results showed that through the function of CLC strategy, the LIBs could approach a target temperature with no additional consumption of energy at 253.15K. Meanwhile, with a pulse width ≤0.01s, a robust control can be achieved in the process, thus eliminating the unstable values of the temperature gradient. However, experimental factors such as target value, energy consumption, cell durability, and ambient temperature still require further research in the future in order to implement the commercial application of electric vehicles.

According to Luo et al. [9] , the existing self-heating systems face a issue of slow heating rate. To deal with this disadvantage, in the research of Luo et al. [9], a battery self-heating system based on both internal impedance of battery and resistance of conductive phase change material is proposed. A fast heating rate of 17.14°C/min as well as a safe functioning state of charge(SOC) range of 20%-100% are provided by this system. Moreover, experiment result shows that effective energy of battery pack is augmented by more than five times after preheating at -20°C, which indicates good effectiveness and a applicable working range of temperature. For analyzing and controlling the relationship between the energy consumed in preheating the battery and the energy improvement in the battery, an energy conversion model is also built in the system. It assists the whole system to obtain the optimum energy-efficient strategy in the preheating process.

In the study of Lin et al. [10], the quick self-heating rate (5.9 °C/min), better battery performance, and high efficiency of preheating (78.75%) are realized by a sandwich heating structure. In such a structure, the two large-area sides of the battery are covered with metal sheets. When the batteries are packed together, they form a stacked structure like a sandwich. This structure was originally designed for the LIBs on the fuel cell buses to achieve a quick start at cold temperatures. However, the researchers explain that it can be applied to pure electric vehicles as well.

4. External preheating

Through external preheating device, LIBs are preheated from outside instead of inside, as the name indicates. Commonly, the external preheating device can not only preheating the batter, but also play an important role in the battery cooling system. Therefore, external preheating face more problems in balancing the preheating and cooling system which is a point for further study. This section will be about the most basic external preheating, which includes air, liquid, and PCM preheating. The process and results of the research, as well as the advantages and drawbacks, are discussed.

4.1. Air preheating

The preheating system utilizing air to transfer heat is highlighted with the features of good reliability, easy maintaining, low price and convenient installation. A typical air preheating system is built in the study of Ji [11]. The system includes battery pack, fan, air channel, air heater and control component. In such a system, the air is heated by air heater firstly using energy provided by external source and battery pack, after which the warm air is driven by the fan and flows through the air channel to surround the battery and transfer heat to the battery pack. Thus, through convection heating, the temperature of the battery pack raises. In their study, the effects of battery voltage and heater resistance receive much attention. The result shows that the time needed to heat the battery to a proper working temperature increases by 2.5 times when the heater resistance doubles (from 0.4Ω to 0.8Ω), which illustrates the importance of regulating the heater resistance to improve preheating efficiency. Generally, the air preheating system is applied to automobile industry due to the advantages mentioned above but limited by its drawbacks of noise and low thermal conductivity which induces unsatisfactory temperature uniformity.

4.2. *Liquid preheating*

Liquid preheating system is known for its high thermal conductivity and high specific heat compared to air preheating system and heat the battery in a more rapid speed, heating the battery in a more rapid speed and implementing better temperature uniformity inside the battery [12]. A typical liquid preheating system contains heater, pump, liquid tube and control component. When it works, the liquid is heated by heater and then pumped through the liquid tube to the battery where the heat is transferred and the battery temperature is raised. In the research of Wang et al. [13], a liquid immersing preheating system was established to conduct an evaluation focusing on its performance and observing the the influence parameters. Several key elements are considered, including rate of temperature rising, energy density, temperature uniformity, battery gap and number, flow rate, inlet and outlet location. Simulation showed that the LIPS is able to realize a temperature rise rate of 4.18 °C/min starting from -28 °C and, at the same time, keep a small difference in the battery temperature (<4 °C). It was also detected in the experiment that the fluid flow velocity and battery number affect the preheating rate to a large extent, which indicated further research.

Although liquid preheating systems have the advantages of high thermal conductivity and specific heat capacity, they make the design and manufacturing of electric vehicles more complex, resulting in an increase in cost. Meanwhile, it also faces the issue of the high requirement for sealing, and the potential damage caused by LPS to the battery is not studied clearly.

4.3. *Phase change material preheating (PCM preheating)*

Phase change material refers to material that can changes the state of matter and provides latent heat while the temperature is constant. The process of changing the physical properties is called the phase transition process, when the phase change material absorbs or releases a large amount of latent heat. PCM is applied to electric vehicles in the year 2000 [14]. The battery installed with PCM works in better temperature uniformity condition and has an extended cycle life [15]. Compared to other preheating methods, the PCM preheating is cheaper and simpler in structure. Nevertheless, the main disadvantage of PCM is low thermal conductivity which results in low heating rate. Due to this feature, improving the thermal conductivity of PCM become a hotspot for researchers in recent years and the PCM is now usually used along with other materials such as graphene and graphite matrix. For example, in the reference[3], they used expanded graphite/polymer composite phase change material to model a thermal management construction for LIB, which possesses high thermal conductivity(19.3 Wm^{-2}/K). The battery energy is used for heating at a rate of 20.5 °C/min when the temperature is -20 °C. After the battery is heated to a proper working temperature, the PCM can keep on releasing heat to keep the battery at a normal temperature and, consequently, a long-term normal function situation. The result shows that there appears to be a 35.5% increase in discharge capacity at -20 °C and at the 1°C discharge rate compared with the situation without preheating treatment. In addition to the preheating function, the PCM in this model also plays a vital role in dissipating the excessive heat of the battery when operating in a high-temperature environment.

Ling et al. [16] study a different preheating strategy which actively control the heat storage and heat release of PCM by taking advantage of the subcooling phenomenon. Specifically, when PCM is in subcooling case, the energy stored in PCM cannot easily release to the surrounding environment. When the battery needs to work, a trigger device is controlled to break the stability of PCM, leading a fast crystallization which dissipates large amount of heat and heat the battery in a rate of 7.5°C/min. This strategy makes the PCM heating method controllable, active and much more efficient, improving the PCM to be a competent part in preheating system as well as in battery thermal management system.

In short, PCM preheating has the advantages of low cost and a simple structure. It can realize high thermal conductivity when combined with other materials like graphite and graphene. Researchers are also recently experimenting with more solutions to optimize the applicability of PCM. Generally, it is a highly potential material that can be a vital part of future electric vehicles.

5. Conclusion

Serving as the core energy source of the electric vehicles, the issues related to LIBs are highly linked to the development of EVs. The problem of LIBs attenuation at low temperature must be solved for the future advancement of EVs. The preheating system is one of the most commonly used method to improve the low temperature performance of the LIBs and to maintain the driving range of EVs in cold climate regions to a great extend. In this review, a brief explanation about LIBs and the rationality of applying the the preheating method are firstly mentioned. Then, both internal and external preheating methods are discussed and their corresponding recent studies are illustrated. The major advantages of the internal preheating system are its high preheating speed, excellent energy efficiency, and ability to achieve good temperature uniformity. At the same time, it is criticized on account of its complex technology and potential safety issues. However, these are important points requiring further research. The external preheating system is relatively cheap and safe but more studies should be done to enhance the competence in achieving good battery temperature uniformity and to minimize the structure which saves more space and mass for EVs. Furthermore, as the electric vehicles need to run among a large temperature range and are applied in both freezing and sweltering zones, the strategy in making preheating and cooling system cooperate together in EVs without much negative effect on each other is also significant point in the progress of battery thermal management system.

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