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Use of Lithium-ion batteries in environmentally friendly vehicles

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Abstract

The concern for the environment and energy has led to a significant increase in research on electric vehicles (EVs) and hybrid electric vehicles (HEVs). The main challenges that need to be addressed to popularize these advanced vehicles are related to the battery. Since the early 1990s, we have been actively promoting research and development on batteries for environmentally friendly vehicle applications. Initially, the focus was on lithium-ion batteries as a potential solution to the critical battery issue mentioned earlier. Through extensive theoretical studies and numerous experimental demonstrations, we have successfully demonstrated that the potential of lithium-ion batteries exists and can be realized. This has opened up new possibilities and values that cannot be achieved with conventional batteries. This article aims to clarify the specific performance requirements of advanced batteries for EVs or HEVs, with a particular emphasis on the critical aspects of thermal design and construction for ensuring system stability. Furthermore, it highlights the significant improvements made in the power output of lithium-ion batteries for their application in HEVs.

Keywords: Li-ion Battery; Hybrid Electric Vehicles; Electric Vehicles; Nickel-Cadmium Batteries

1. Introduction

Efforts are currently underway to introduce eco-friendly vehicles to the market through research and development. One of the primary challenges associated with these advanced vehicles is addressing powertrain issues to ensure sufficient power output that meets the vehicle's performance requirements while also maximizing energy efficiency. To accomplish this, it is crucial to enhance the performance of drive components and minimize resistive losses. Our primary focus has been on lithium-ion battery systems due to their potential as future power sources for environmentally friendly vehicles [1]. Since 1992, we have been conducting a comprehensive program to research and develop lithium-ion batteries suitable for various types of eco-friendly vehicles. Throughout this process, we have demonstrated that lithium-ion batteries not only possess excellent capacity but also exhibit high power characteristics. In order to assess the suitability of lithium-ion batteries for different vehicle types, we have conducted thorough studies to optimize battery capacity and output. The analysis of internal battery resistance, particularly in terms of electrode reactions and electron and ion transport, plays a crucial role in studying power output. By reducing internal resistance, we can enhance battery output, improve energy efficiency [2], and minimize heat generation within the battery, ultimately resulting in greater reliability.

The thermal design is a crucial factor to consider when it comes to vehicle application. It is necessary to take into account the usage environment, as the battery will experience continuous, high-current charging and discharging for an

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extended period. Therefore, a proper thermal design is vital. Our research has demonstrated that lithium-ion batteries offer exceptional thermal design capabilities, which meet this requirement. Consequently, we can develop a compact powertrain system that is anticipated to enhance vehicle performance [3]. This article delves into the optimization of lithium-ion batteries and explores their viability in different environmental vehicles, with a specific focus on battery performance and system design, particularly thermal considerations.

2. The output characteristics of lithium-ion batteries can be described in various ways

2.1. The Evolution of Secondary Battery Performance throughout History

There are two fundamental indices of battery performance: (1) energy density, which indicates how much energy a battery can store, and (2) power density, which indicates its maximum output. For example, in the case of electric vehicles (EVs), autonomy is It depends on the energy storage capacity of the battery, which calls into question the magnitude of the battery's energy density [4]. By contrast, in the case of hybrid electric vehicles (HEVs), which are equipped with a generator, the ability to supply energy for acceleration and accept regenerated energy during deceleration is more important than the amount of energy the battery can store. Figure 1 shows a historical summary of the improvement achieved in the energy density of typical homes. Secondary batteries for use in electrical appliances.

Before the 1990s, lead-acid batteries and nickel-cadmium batteries were representative examples of secondary batteries. The energy density of nickel-cadmium batteries did not exceed 50 Wh/kg at most. In the early 1990s, nickel-metal hydride batteries and lithium-ion batteries successively appeared, and the energy density of small batteries for consumer electronics has increased nearly fourfold in about the past 15 years.

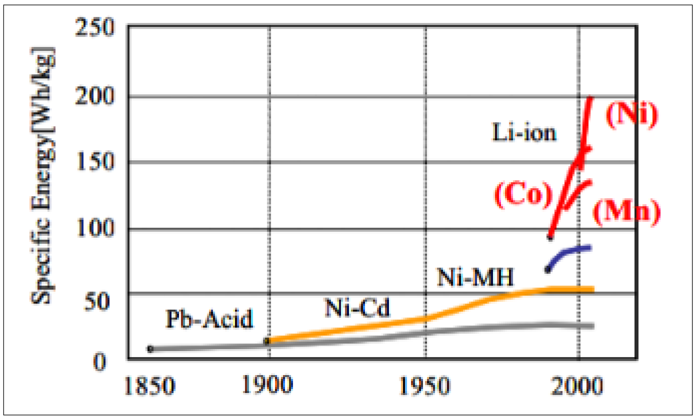

Figure 1 Specific energy of secondary batteries for electric appliances

2.2. Energy Consumption Inside Batteries

The energy consumption within a battery consists of the part attributable to the reactions of the battery and the energy losses that accompany charge transport, that is, electron conduction or ion conduction. The smaller these values are, the less energy is consumed within the battery, reducing internal resistance and increasing the battery's intrinsic output voltage [5]. Regarding the structure of the electrode, the reduction in the thickness of the active material layers reduces resistance to the passage of lithium ions and electrons through the layers. However, this would gradually increase the relative proportion of energy consumption accounted for by components not directly involved in energy storage, such as separators or current collectors, leading to a decrease in the energy density of the battery [6].

2.3. Battery Output Simulation

More accurate predictions of a battery's internal resistance values are needed to more accurately determine internal energy consumption. Resistance values are mutually dependent on variables such as ion concentration and current value. Consequently, they can only be obtained by solving equations consisting of many related physical quantities. Based on this way of thinking, a battery output simulation model that combines battery reactions and charge transport was built, as shown in Fig. 2. [7].

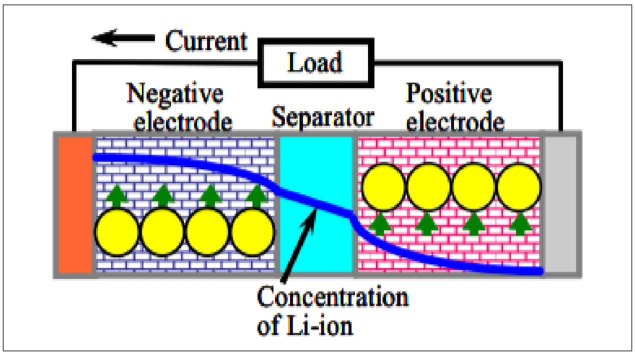

Figure 2 Battery simulation combined with lithium diffusion

To validate this simulation model, electrode prototypes were manufactured and evaluated in tests. Then a comparison of the experimental and calculated results was made. As an example, Figure 3 compares the calculated and experimental discharged capacity for two different levels of discharge current [8]. A good agreement is observed between the experimental and calculated values.

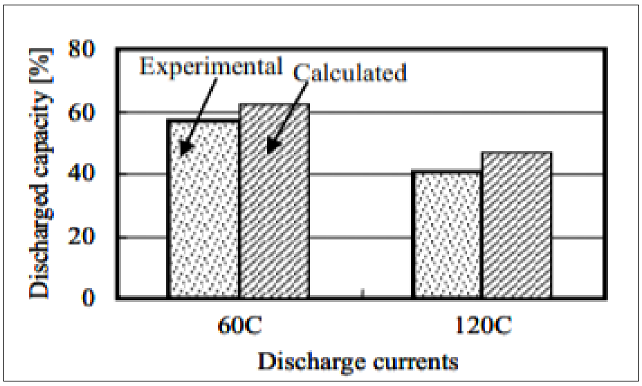

Figure 3 Comparison of experimental and calculated discharge capacity

2.4. Optimization of Battery Output and Capacity

Based on the above knowledge, the relationship between battery production and capacity was examined. Figure 4 shows the discharged capacity as a function of electrode thickness. The results indicate that the discharged capacity at the same discharge current decreases with increasing electrode thickness.

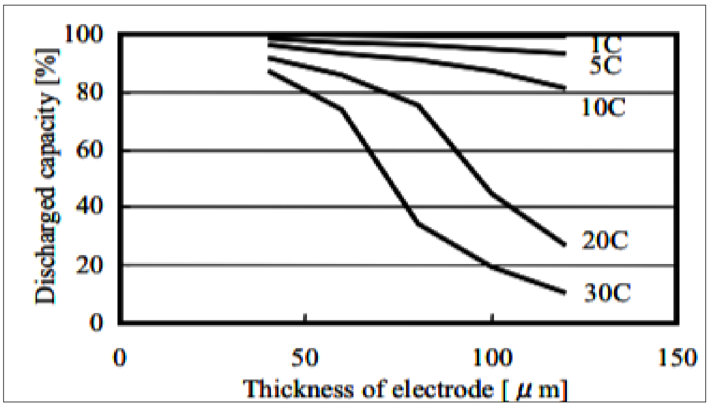

Figure 4 Discharged capacity with various electrode thicknesses

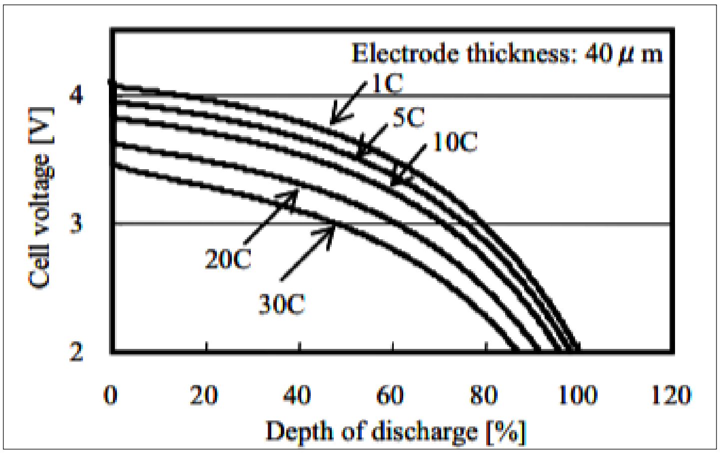

Figure 5 Voltage drop with various discharge currents

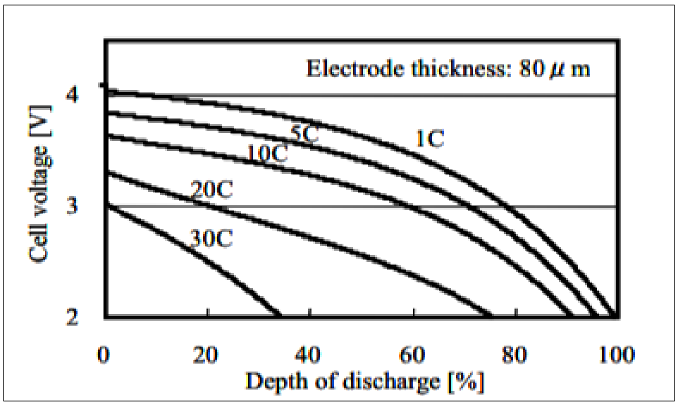

Figure 6 Voltage drop with various discharge currents

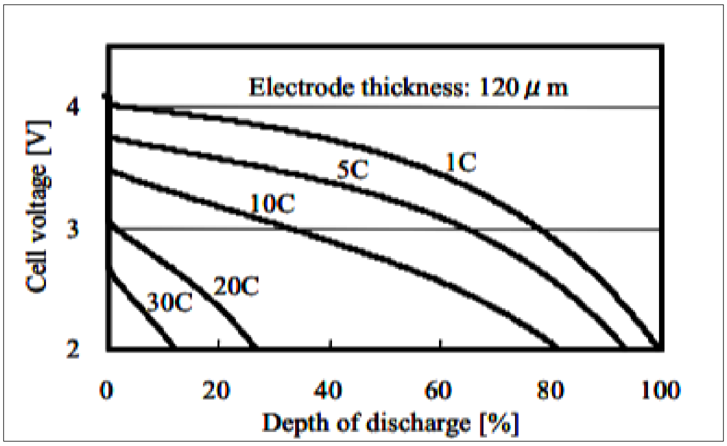

Figure 7 Voltage drop with various discharge currents

To investigate the reason for that decrease, the change in battery voltage during discharge was calculated under the same current conditions [9]. The results are shown in Figs. 5-7 for different electrode thicknesses. The results indicate that following the voltage drop immediately after the start of discharge, the terminal voltage of the battery gradually decreases and that the difference in this voltage drop increases with increasing discharge current. The main reason for the decrease in the maximum output that can be obtained from the battery is attributed to this voltage drop at the terminals. It is assumed that in the region where a relatively large current value is required [10], the diffusion of lithium ions in the electrodes cannot follow the required discharge current, giving rise to an ion concentration gradient that results in a voltage drop.

Based on the above research, the relationship between the maximum output of the battery and the energy density was simulated. This relationship was calculated for different types of vehicles using the same material property parameters. For electric vehicles or different types of HEV systems, the relationship between maximum output and battery capacity differs depending on the range of the vehicle and its power source [11]. As the results in the figure indicate, lithium-ion batteries achieve a good balance between power and capacity in wide use range as a result of optimization of the electrode structure.

3. Thermal design of lithium-ion battery systems

3.1. Thermal Behavior of Battery Systems

Not only does the level of discharge current required differ between different types of environmental vehicles, but the charge/discharge frequency and continuous duration also vary considerably. The amount of heat generated by the battery increases as the power output demanded by the powertrain increases [12]. In addition to ensuring the necessary power and capacity, the battery system design must also ensure that the system is thermally viable.

Heat generation within a battery can be attributed to joule heat originating from the internal resistance accompanying charge and discharge processes and reaction heat produced by charge and discharge reactions. This heat generation raises the temperature of the battery, and continued exposure to high temperatures could accelerate battery degradation. To avoid this possibility [13], the increase in battery temperature must be suppressed by applying an appropriate cooling system.

3.2. EV and HEV Driving Modes

The operating conditions of a battery system differ substantially depending on the type of environmental vehicle involved. In an electric vehicle, the battery is continuously discharged, but the specific power required relative to the battery capacity (i.e., the power-to-energy (P/E) ratio) is small. In a series hybrid (SHEV), assuming the battery provides the energy to drive the vehicle, the influence of heat generation increases because a smaller battery pack than that of an EV discharges current to drive the traction motor. Additionally, the battery must be able to accept a large charging current for a short period of time [14], which is another aspect that increases the importance of thermal design. In a parallel hybrid (PHEV), the battery must be able to discharge and accept large currents instantaneously to support vehicle acceleration and deceleration. However, the battery's operating time is shorter and the absolute amounts of energy are smaller, so the P/E ratio is higher [15]. There is a lot of heat generation during charging and discharging due to the large currents involved, but there are long periods of time when the battery is not charged or discharging and can cool down during these intervals.

3.3. Thermal Characteristics of Batteries

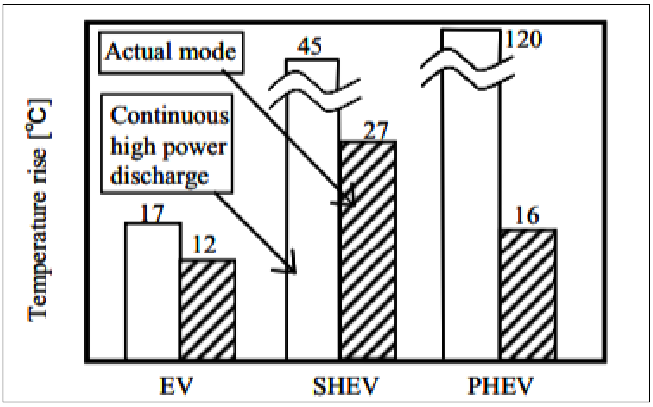

Figure 8 Battery temperature rise with various vehicles

A study was conducted to analyze the thermal properties of lithium-ion batteries in relation to different usage conditions in electric vehicles. The findings are illustrated in Figure 8. The research initially focused on a driving scenario where the battery undergoes continuous discharge and handles substantial currents. The temperature increase in the battery under these conditions is displayed in the left-bar graphs of the figure. Each graph demonstrates the equilibrium temperature rise, calculated by dividing the battery's heat generation under specific vehicle operating conditions by the thermal radiation coefficient and area. In this mode, it is observed that the PHEV battery, subjected to high current discharges, experiences the most significant temperature rise, indicating severe thermal stress. However, to accurately assess the battery's temperature increase [16], factors such as charging time, discharging time, and rest intervals need to be considered for each system under this driving condition.

The shaded bar graphs on the right side of the figure show the temperature rise accounting for these factors. These graphs reveal the highest temperature increase experienced by the battery in this driving mode [17]. Despite the PHEV battery enduring high current discharges and extended charge-discharge suspension periods, resulting in enhanced cooling effects, the SHEV battery faces adverse thermal conditions due to prolonged high-current charging and discharging cycles. Nevertheless, the calculations suggest that the SHEV battery design remains thermally feasible [18]. The temperature rise variation in each vehicle during this driving mode is shown in the right bar graphs of Figure 9.

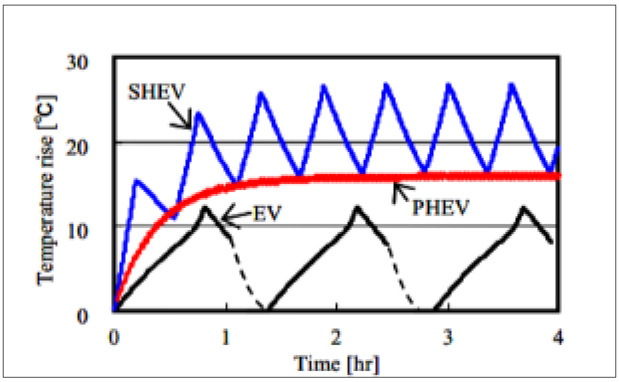

Figure 9 Battery temperature rise with various vehicles

3.4. Thermal Characteristics of Aqueous Electrolyte Batteries

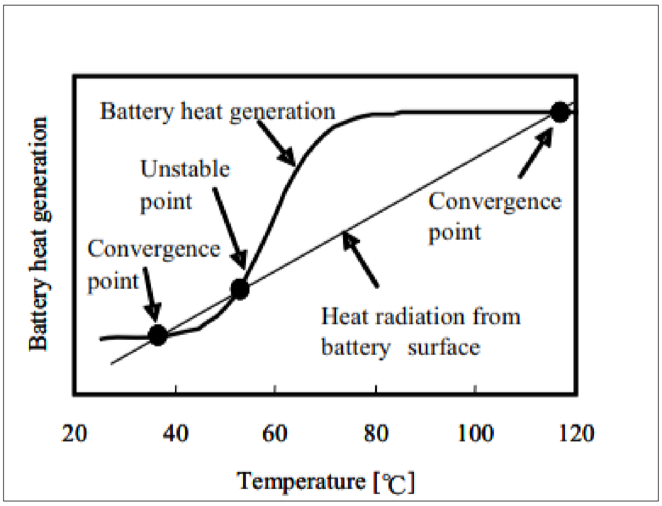

Figure 10 Analysis of battery equilibrium temperature for medium-size to large batteries

The preceding sections have detailed the findings of lithium-ion batteries utilizing an organic solution as an electrolyte [19]. Heat generation in lithium-ion batteries while charging or discharging can be categorized into reaction heat from electrochemical reactions and joule heat from internal resistance. However, for batteries using an aqueous solution as the electrolyte, consideration must also be given to the electrolysis (and recombination) of the water acting as the solvent. As the battery nears the end of charging or experiences temperature elevation, among other scenarios, electrolysis can be accelerated, leading to further temperature rise [21]. This principle is illustrated in Fig. 10, with battery temperature plotted on the horizontal axis. The linear representation on the graph depicts the heat dissipation from the battery surface, and the points where it intersects with the battery heat generation curve signify the equilibrium temperature. In this figure, three such intersection points exist. The midpoint intersection on the graph represents an unstable solution, while the intersections on the lower temperature side (left) and higher temperature side (right) denote stable solutions. If the battery temperature is below the central solution [23, 24], it moves towards the stable solution on the lower temperature side; if it surpasses this point, it shifts towards the higher temperature side. Notably, the absence of heat dissipation at the intersection point of the line and the x-axis designates room temperature, suggesting that repositioning the linear representation alters the room temperature. Consequently, depending on the operational circumstances, there is a chance for the equilibrium temperature to abruptly transition from the lower-temperature side to the higher-temperature side [22]. Figure 11 provides a sample of the calculated battery temperature for an aqueous solvent electrolyte in a SHEV application [25]. While this is purely a hypothetical scenario, it implies that battery temperatures might surge significantly due to the heat generated by the water electrolysis reaction. Owing to their inherent characteristics, lithium-ion batteries do not encounter such temperature fluctuations. Prior findings have indicated that adjusting the attributes of lithium-ion batteries renders them suitable for deployment in various eco-friendly vehicles [26], from electric vehicles to PHEVs, in terms of both energy output and thermal stability.

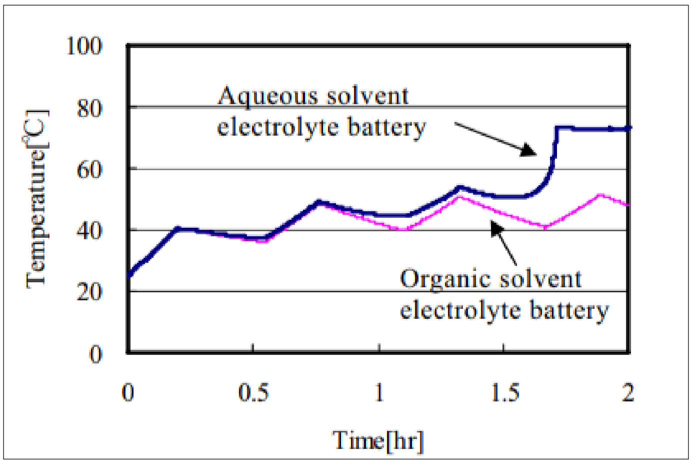

Figure 11 Comparison of battery temperatures in SHEV application

4. Conclusion

A simulation model combining electrode reactions and charge transport was built in order to predict battery performance and was used to examine energy production and capacity in particular. It was shown that changing the electrode parameters of lithium-ion batteries makes it possible to create energy source systems that are suitable for application in a wide range of envisioned green vehicles. Furthermore, when used in combination with thermal simulations, it is possible to examine battery systems from the perspective of their thermal design. The results of the present study have shown that the battery systems examined are sufficiently viable for practical use. Consequently, it is concluded that lithium-ion battery systems are the most suitable energy sources for use in a wide variety of environmental vehicles.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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