Advancements and Challenges of Lithium Battery Technology in Electric Aircraft

Chenhao Li*

Zibo No.11 Middle School, Zibo, 255035, China

*Corresponding author: caodongjun@ldy.edu.rs

Abstract. The demand for sustainable energy solutions has heightened the focus on electric aircraft as an effective approach to reduce reliance on fossil fuels and mitigate environmental issues like global warming. Among various battery technologies, lithium-ion batteries (LIBs) have emerged as a key contender for powering electric aircraft due to their high energy density, lightweight properties, and superior electrochemical performance. Lithium's low electrochemical potential and high electropositivity allow these batteries to deliver greater voltage, energy density, and charge/discharge efficiency compared to traditional lead-acid and nickel-metal hydride batteries. Additionally, LIBs exhibit fast charging, low self-discharge rates, and long operational lifespans, making them ideal for use in electric vehicles and other high-performance applications. However, the challenges of battery safety, energy density limitations, and environmental concerns regarding their production and recycling must be addressed to unlock their full potential in aviation. Continued advancements in these areas are crucial to achieving sustainable, high-performance electric aircraft.

Keywords: Lithium-ion battery; electric aircraft; energy density.

1. Introduction

In today's society, people are gradually realizing the importance of the environment. Many environmental problems, such as global warming and climate change, have seriously affected human life. The main cause of this air pollution and environmental effects is the burning of fossil fuels for energy and power generation, which produces some greenhouse gases (mainly carbon dioxide, CO_2 and methane, CH_4) [1]. In order to reduce the use of fossil fuels, people are starting to focus on cleaner and Non-polluting electricity. Batteries are being studied to replace fossil fuels to power cars and airplanes. At present, scientists have studied many different types of batteries, but the most promising is lithium batteries. The significant appeal of lithium-ion technology stems from lithium's status as an extremely light metal, characterized by a molar mass of 6.941 g/mol and a density of 0.51 g/cm^3. Its electronic configuration follows the (He)2s^1 pattern. Lithium metal boasts an impressive specific capacity of 3860 mAh/g, and the Li^0/Li^+ couple exhibits exceptional electrochemical reactivity, with a standard redox potential of -3.04 V relative to the H_2/H^+ reference. As a result, lithium batteries achieve voltages that substantially exceed those of lead-acid and nickel-metal hydride batteries, owing to lithium's position as the most electropositive element naturally occurring on Earth [2].

Li-ion batteries also have many advantages in that they can provide high power capacity in a small size and weight, making them widely used in portable electronic devices and electric vehicles. Lithium batteries have a low self-discharge rate compared to other batteries, which means that lithium batteries can be kept charged for long periods. Lithium batteries also have a shorter recharge time than other batteries, which is particularly important for devices that require frequent recharging. Lithium batteries can retain a high capacity even after multiple charges and discharges, giving them a longer life than other batteries. However, LIBs also have many challenges and limitations. Li-ion batteries can pose safety risks if overcharged, over-discharged or mechanically damaged, such as overheating, fire or even explosion. To protect Li-ion batteries from overcharging and short-circuiting, Li-ion batteries require complex protection circuitry, which significantly increases the cost and complexity of the battery. The production and disposal of lithium batteries can be harmful to the environment. Although some metals in lithium batteries can be recycled, the current recycling rate is not high, which limits the sustainability of lithium batteries.

At present, lithium batteries are being studied for electric aircraft because of their small size and mass compared to other batteries. In the case of lithium batteries and fossil fuels with the same energy density, lithium batteries are about 50 times heavier than fossil fuels. At the same time, for the same specific energy, the battery takes up 18 times the volume of fossil fuels. The current development goal is to reduce the gap caused by the energy density between electric aviation and conventional aircraft [3].

2. Working Mechanism of Lithium Batteries

2.1. Composition and Structure of Lithium Batteries

Lithium batteries store and release energy by moving lithium ions between the positive and negative electrodes of the battery. The main components of a lithium battery include the positive electrode, which is usually composed of lithium metal oxides ($LiCoO_2$ or $LiFePO_4$). The negative electrode is typically made of graphite or other carbon materials, and the electrolyte is the medium that allows the lithium ions to move. The diaphragm is designed to allow lithium ions to pass through while preventing short circuits caused by direct contact between the electrodes [4].

2.2. Production Processes and Techniques for Lithium Batteries

LIBs are manufactured in a series of delicate steps: First, thin sheets of metal are coated with positive and negative active materials. These coated sheets are then wound together with a spacer in between. The rolled components are placed in the battery case, which is then filled with an electrolyte solution. Finally, the case is sealed, and the battery is complete. The fabrication of Li-Ion batteries generally involves five key stages:

i) Preparing the electrode materials by mixing, kneading, coating, pressing, and slitting for both the positive and negative electrodes.

ii) Assembling the cell by winding the positive electrode, negative electrode, and separator together.

iii) Placing the wound electrode assembly into the battery casing and injecting the electrolyte.

iv) Sealing the casing to enclose the cell.

v) Finishing with formation, aging, and selection of the cells to ensure performance and quality standards [5].

3. Feasibility and Application of Lithium Battery Technology in Aircraft

3.1. Key Requirements for Deploying Lithium Batteries in Electric Aircraft

In the context of exploring electric vertical take-off and landing (eVTOL) aircraft as a transformative technology for future transportation systems, this study provides an in-depth analysis of the specific battery performance requirements for eVTOL aircraft. Given the unique operational characteristics of eVTOL aircraft, their battery requirements are significantly higher than those of electric vehicle batteries in terms of energy density, power density, fast charging capability, cycle life and safety, as shown in Fig. 1. In particular, this study highlights the importance of fast charging technology, stating that it is decisive for optimizing aircraft and battery design, reducing costs and improving the efficiency and economics of aircraft operations. In order to meet the high standard of battery performance required for eVTOL aircraft, two high-energy density Li-ion battery designs are proposed in this study. These batteries are experimentally verified to be able to provide eVTOL aircraft with enough energy to complete an 80-kilometer flight mission in 5 to 10 minutes and to maintain stable performance during more than 2,000 rapid charging cycles. These research results not only provide a scientific basis for the battery technology of eVTOL aircraft but also point out the direction for future battery development in the field of electric aviation [6].

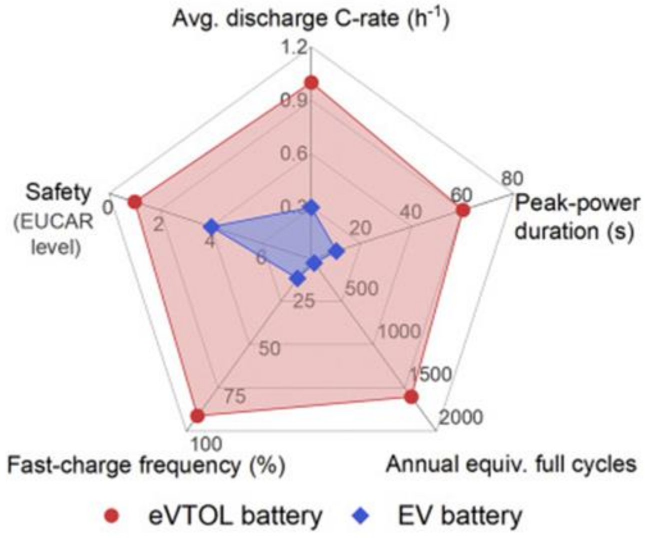

Fig. 1 Different battery requirements for eVTOL and electric vehicles [6].

3.2. Principles Governing the Application of Lithium Batteries in Aviation

Lithium batteries in aviation applications need to meet some specific performance requirements and safety guidelines to avoid fires. In the US commercial air transport sector, a comprehensive review spanning some 20 years identified a total of 274 documented thermal runaway events. Notably, the vast majority (76 percent of the total) were reported to have occurred after 2015. The primary manifestation of these events was fire. In addition, the most common source implicated in these thermal runaway events was unidentified loose lithium batteries [7,8].

4. Cathode Materials in Lithium Batteries

The cathode material for lithium aviation batteries is usually a composite material made up of a variety of metal oxides that provide high voltage and high capacity, thereby increasing the energy density of the battery.

4.1. $LiCoO_2$ Layer Structure

Layered oxides consist of layers of metal oxides stacked on top of each other. For example, lithium cobaltite (LCO) has the chemical formula $LiCoO_2$, as shown in Fig. 2. Each metal oxide layer consists of two layers of oxygen atoms, with transition metal atoms filling the gaps between them. Lithium ions are embedded in the gaps between these metal oxide layers to form a thin lithium layer. Lithium ions move within each lithium layer to achieve two-dimensional diffusion. The mobility of lithium ions in the layered cathode material varies with the state of charge and discharge of the battery.

4.2. $LiMn_2O_4$ Layer Structure

Spinel Oxides: Lithium manganese oxide (LMO), with the chemical formula $LiMn_2O_4$, is a representative spinel oxide. In this structure, manganese atoms are positioned at the octahedral sites within a cubic lattice of oxygen atoms. Lithium ions facilitate three-dimensional diffusion by migrating through available tetrahedral and octahedral voids within the lattice framework.

4.3. $LiNiO_2$ Layer Structure

The compound $LiNiO_2$, with a stoichiometric composition, crystallizes in the rhombohedral system with space group R3m. Within this structure, lithium and nickel ions are strategically positioned at the octahedral 3a and 3b sites, respectively, adopting a face-centered cubic (fcc) packing arrangement. This particular configuration endows the material with a two-dimensional pathway facilitating the intercalation and de-intercalation of lithium ions, which is essential for its electrochemical performance in lithium-ion battery applications. The structural framework not only ensures the stability of the material during charge-discharge cycles but also optimizes the ionic conductivity, thereby enhancing the overall battery performance [9].

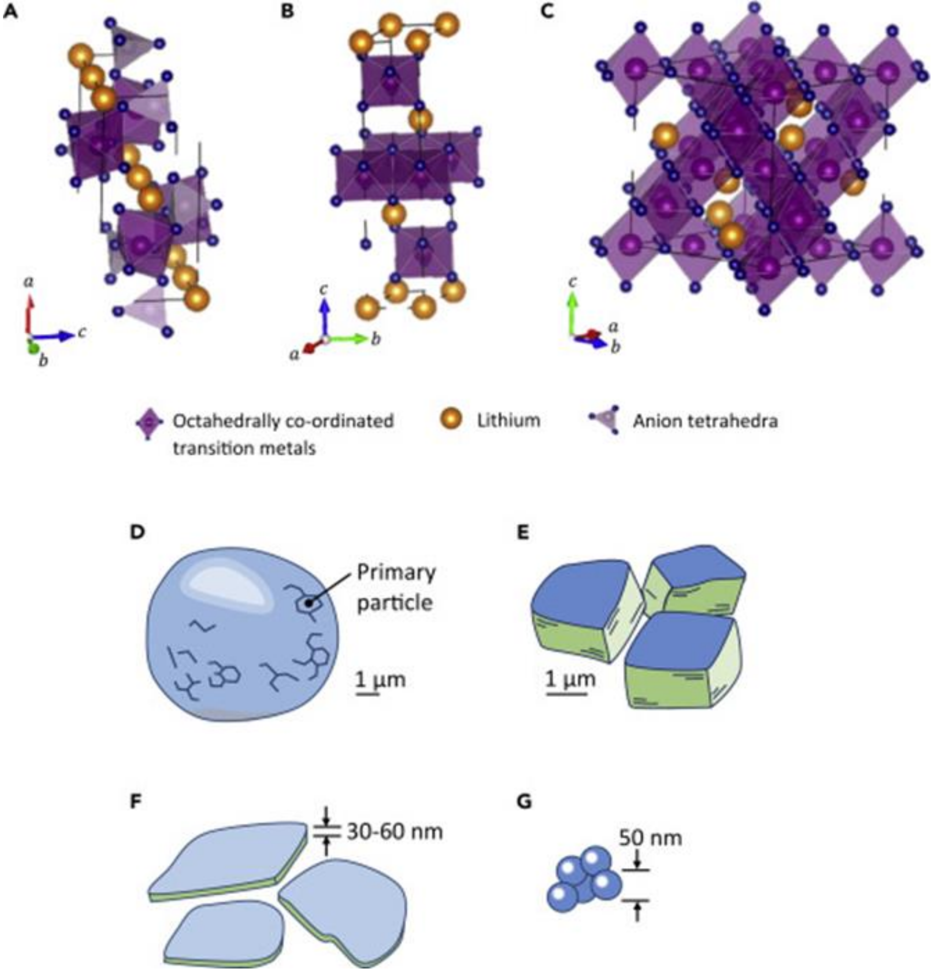

Fig. 2 The atomic structures of cathode materials and different cathode particle architectures [8].

5. Anode Materials in Lithium Batteries

Anode materials for LIBs mainly include graphite, silicon-based, tin-based, lithium titanate and alloys, etc., and research is dedicated to improving energy density and cycle stability.

5.1. Graphene-Based Materials

Graphene, a monolayer of sp^2-hybridized carbon atoms in a hexagonal lattice, has become a focal point of research since its initial discovery. Its unique set of properties positions it as a promising candidate for a multitude of applications. Notably, graphene exhibits an exceptionally high intrinsic carrier mobility of 350,000 $cm^2 V^{-1} s^{-1}$, which is a critical parameter for high-speed electronic devices. Additionally, it possesses remarkable thermal conductivity, quantified at approximately 3000 $W m^{-1} K^{-1}$, making it an excellent material for thermal management solutions. The theoretical specific surface area of graphene is an impressive 2630 $m^2 g^{-1}$, a feature that is advantageous for applications in energy storage and catalysis. Furthermore, its mechanical strength is unparalleled, with graphene being one of the strongest materials known, which suggests potential in the realm of composite materials and structural applications. These properties collectively underpin graphene's significance and drive ongoing research into its integration across various industrial sectors [10].

5.2. Silicon-Based Materials

Silicon (Si) has emerged as a highly prospective anode material for LIBs, presenting significant advantages over traditional graphite anodes. The superior gravimetric capacity of Si, reaching up to 4200 mA h g^{-1}, along with a volumetric capacity of 2400 mA h cm^{-3}, can be attributed to its reaction with lithium to form $Li_{4.4}Si$. This substantial capacity enhancement is a key factor driving research and development efforts in this area. Furthermore, Si demonstrates a lower electrochemical reaction potential of less than 0.5 V versus Li/Li+, which correlates with improved safety characteristics. Additionally, Si is recognized for its environmental benignity and natural abundance, offering a more sustainable and economically viable alternative to graphite. These attributes position Si as a compelling candidate for next-generation anode materials in LIBs, with the potential to significantly enhance the energy density and safety profile of lithium-ion battery technologies [11].

5.3. Tin-Based Materials

Tin-based compounds (TBCs) have garnered significant interest in the realm of LIBs due to their economic synthesis and abundant resource availability, which are more favorable compared to other anode materials such as Si and germanium. Despite these advantages, the application of TBCs in LIB anodes is impeded by two critical issues. First, the pronounced volume fluctuations experienced during the lithiation/delithiation processes lead to the pulverization of TBCs, which can severely degrade the structural integrity of the anode and limit cycle life. Second, the formation of solid electrolyte interphase (SEI) films, which includes the irreversible formation of Li_2O or Li_2S, results in relatively low Coulombic efficiency. These challenges necessitate the development of strategies to mitigate volume changes and enhance the stability of the SEI, thereby improving the overall performance and cyclability of TBC-based anodes in LIBs [12].

6. Conclusion

LIBs are high-energy density rechargeable batteries that work by relying on the movement of lithium ions between the positive and negative electrodes to achieve charging and discharging. The advantages of this type of battery include high energy density, high discharge power, long cycle life, no memory effect, and environmentally friendly characteristics. LIBs are widely used in portable electronic devices, electric vehicles, power tools and energy storage systems.

LIBs are composed of anode materials (such as LCO, lithium manganate, lithium iron phosphate, etc.), anode materials (usually graphite), electrolytes and diaphragm. During charging, lithium ions are detached from the positive electrode and move through the electrolyte to the negative electrode and become embedded; during discharge, lithium ions are detached from the negative electrode and return to the positive electrode.

With the development of technology, research on LIBs has continued to deepen, including improving battery safety, energy density, cycle life, and cost reduction.

In terms of applications, LIBs are particularly important in the field of electric motorcycles and aircraft, as they provide the high energy density and power density needed to achieve longer range and good acceleration performance compared to other batteries. However, LIBs still have many problems compared to conventional internal combustion engines, and the main issue at the moment is how to close the energy density gap between LIBs and fossil fuels.

In summary, the development and application of Li-ion battery technologies are promising, and they play a key role in driving the energy transition and achieving sustainable development. With in-depth research and technological advances, people can expect LIBs to be more efficient, safe and environmentally friendly in the future.

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