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# Achieving Electric Aviation with Advanced Battery Technology and Nanomaterials

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**Abstract.** With the continuous development of industry, environmental problems continue to worsen, of which the environmental problems caused by the traditional aviation industry are particularly serious, but there are many problems with electric aircraft that have not been solved. Therefore, this paper explores the realization of electric aviation by using advanced battery technology and nanomaterials. The study found that there are a variety of advanced battery technologies and nanomaterials that contribute to the realization of electric aviation, among which Multi-walled carbon nanotubes(MWCNT)/ graphene-based composite phase change material technology has considerable potential. It has excellent battery thermal management performance and excellent high-power density. However, MWCNT/ graphene-based composite phase change material technology also has shortcomings at present, such as the production process is complex and difficult to mass produce. Although there are still many challenges, this paper believes that these challenges will be solved to enable electric aviation using advanced battery technology and nanomaterials.

## 1 Introduction

The advancement of industrial technology has significantly contributed to the increase in carbon dioxide emissions, posing a severe threat to global environmental health. Notably, the aviation sector is responsible for approximately 3% of worldwide $CO_2$ emissions. However, as other sectors progress towards decarbonization, the aviation industry's share of $CO_2$ emissions could escalate to 22% by 2050. Motivated by environmental conservation objectives, this research explores the potential of electric aircraft within the aviation sector. Recent years have witnessed a surge in interest in electric aircraft as a viable strategy to diminish greenhouse gas emissions and alleviate the environmental footprint of traditional aviation practices. Given the escalating demand for air travel coupled with the imperative to address climate change, the pursuit of efficient and sustainable electric aviation technologies emerges as a critical avenue for environmental protection.

Electric aircraft offer substantial benefits, including significant reductions in environmental pollution and lower operational costs for the aviation industry, thereby facilitating the emergence of new markets, such as short-haul flights. Furthermore, electric aircraft contribute to decreased fuel consumption and a reduced reliance on non-renewable energy sources. The development of electric aircraft technology holds considerable significance for the aviation industry and the global environment at large.

Despite the significant potential of electric aircraft in reducing greenhouse gas emissions, their development is hindered by several critical challenges, particularly concerning battery technology. The primary issue lies in the energy density of current battery technologies, which is substantially lower than that of conventional aviation fuels. This limitation restricts electric aircraft from performing long-haul flights, which are crucial to the aviation industry. Moreover, the development of adequate charging infrastructure presents another significant challenge. Electric aircraft necessitate a network of charging stations equipped with fast-charging capabilities to ensure their practicality and feasibility for widespread use. The establishment of such an infrastructure is vital for the advancement of electric aviation. Safety concerns also play a critical role, especially regarding the use of lithium-ion batteries, which are prone to risks due to their flammable electrolytes. Ensuring the safety and reliability of these batteries is paramount for the successful integration of electric aircraft into the aviation sector.

This study aims to examine the current state of battery technology in electric aviation, identify the obstacles that must be overcome, and explore the potential of nanomaterials to enhance battery performance. By incorporating nanomaterials, there is a possibility to significantly improve energy storage capacity, charging and discharging rates, and overall battery efficiency, paving the way for the advancement of electric aircraft technology.

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## 2 Limitations of traditional battery technology in aviation

### 2.1 Lithium-ion battery

Lithium-ion batteries, which employ lithium ions as charge carriers, are composed of a positive electrode, a negative electrode, a separator, and an electrolyte. The positive electrode typically consists of oxides such as lithium cobalt oxide, lithium manganese oxide, or ternary materials, while the negative electrode is generally made of graphite. The electrolyte usually comprises organic solvents, including carbonates. Lithium ions move through the electrolyte from the positive electrode to the negative electrode during the charging process, whereas electrons move from the negative electrode to the positive electrode. Lithium ions are able to separate and enter the electrolyte as a result of this movement, which also oxidizes the positive electrode material and releases oxygen ions. On the other hand, during discharge, lithium ions from the electrolyte and oxygen ions from the positive electrode material recombine, creating oxides and releasing electrons. These electrons travel from the positive to the negative electrode, powering the external circuit and facilitating the output of electrical energy.

### 2.2 Sodium-ion battery

Sodium-ion batteries, utilizing sodium ions as charge carriers, operate on principles analogous to those of lithium-ion batteries. These batteries are comprised of a positive electrode, a negative electrode, a separator, and an electrolyte. The positive electrode typically employs sodium ion compounds, such as sodium oxide, while the negative electrode uses carbon materials. Organic solvents, like acetone, are commonly used as the electrolyte. During charging, sodium ions migrate from the positive to the negative electrode through the electrolyte, accompanied by electron flow in the opposite direction. This process induces an oxidation reaction at the positive electrode, resulting in the release of oxygen ions from the oxide and the detachment of sodium ions into the electrolyte. In the discharge phase, oxygen ions at the positive electrode recombine with sodium ions from the electrolyte to form oxides, simultaneously liberating electrons. These electrons move from the positive to the negative electrode, powering the external circuit and enabling the output of electrical energy.

### 2.3 Fuel cell

A fuel cell is an apparatus designed to transform chemical energy directly into electrical energy. It comprises a positive electrode (oxygen electrode), a negative electrode (hydrogen electrode), and an electrolyte, which may be a solid polymer membrane or a liquid. The negative electrode utilizes hydrogen as fuel, whereas the positive electrode employs oxygen or air as the oxidant. Within the fuel cell, hydrogen is introduced at the negative electrode, initiating a redox reaction within the electrolyte that generates electrons and hydrogen ions. The electrons traverse from the negative to the positive electrode through an external circuit, facilitating electrical output. Concurrently, hydrogen ions migrate through the electrolyte to the positive electrode, where they react with oxygen to produce water.

### 2.4 Comparison of emerging battery technologies

A brief comparison of the current emerging battery technologies is summarized in Table 1 below:

**Table 1.** Comparison of current emerging battery technologies

| Battery name | Lithium-ion battery | Sodium-ion battery | Fuel cell |
|---|---|---|---|
| advantages | 1.High energy density<br>2.Long service life<br>3.Fast charging speed<br>4.Relatively environmentally friendly | 1.Abundant sodium resources<br>2.High energy density<br>3.Long service life<br>4.High security | 1.High efficiency<br>2.Long service life<br>3..Relatively environmentally friendly<br>4.Renewable resources |
| limitations | 1.The charge and discharge rate is low<br>2.Poor security | 1.The charge and discharge rate is low<br>2.Large volume<br>3.The operating temperature range is narrow | 1.Higher cost<br>2.Poor stability<br>3.Fuel storage and delivery are troublesome |

Current battery technologies employed in electric aircraft exhibit both strengths and weaknesses and while they demonstrate exceptional performance in certain aspects, they nonetheless possess inherent deficiencies that limit their suitability for future electric aviation needs. Notably, safety concerns associated with these batteries are well-documented, exemplified by the battery failure incident involving a Japan Airlines (JAL) Boeing 787 Dreamliner in 2013. In this case, lithium-ion batteries malfunctioned on two Boeing 787 Dreamliners, leading to overheating, smoke, and fire, compelling JAL and All Nippon Airways (ANA) to ground their 787 Dreamliner fleets. Furthermore, the Boeing 737 MAX aircraft experienced two catastrophic crashes in 2019, with one attributed to a defective lithium-ion battery.

In conclusion, the imperative for developing new battery technologies for electric aircraft is evident, underscoring the need for advancements that address current limitations and safety issues.

# 3 Emerging battery materials and technologies

## 3.1 The next generation of cathode materials

A high nickel cathode is considered a promising candidate for the next generation of cathode materials. High-nickel cathodes, characterized by a nickel content exceeding 60%, are prevalent in lithium-ion batteries due to their high specific capacity, energy density, and extended cycle life. Despite these advantages, high-nickel cathode materials are associated with significant drawbacks, including elevated costs and susceptibility to structural changes and polarization during charge-discharge cycles, which detrimentally impact battery performance and longevity. To address these challenges, ongoing research and development efforts are focused on innovative high-nickel cathode materials, such as high-nickel manganese lithium and high-nickel cobalt lithium. These advancements aim to enhance lithium-ion battery performance while concurrently reducing production costs.

Because of its layered structure and lithium-ion composition, lithium-rich layered oxide is also used as a positive electrode material for lithium-ion batteries. Lithium-rich layered oxide cathode materials have specific capacities that can surpass 250 milliampere-hours per gram. This makes them a prime contender for the creation of high-specific energy lithium-ion batteries. [1]. These materials are preferred because of their long cycle life, high specific capacity, and energy density. Lithium cobalt oxide, lithium nickel oxide, and lithium manganese oxide are common variations. Although more expensive, lithium cobalt oxide offers better specific capacity and energy density. Even though lithium nickel oxide has a slightly lower capacity and cycle life than other options, it is more affordable. The most cost-effective material, on the other hand, is lithium manganese oxide, despite its poor cycle life and capacity. Lithium-rich layer oxide is one of the positive electrode materials of lithium-ion batteries with good development prospects. The specific capacity of Li-rich manganese oxide $xLiMO_2 \cdot (1-x) Li_2MnO_3$ (M = Ni, Co, Mn, etc.) can generally reach 250~ 300 mAh/g, and the specific capacity as high as 400 mAh/g has been reported in recent years [2].

## 3.2 Innovative anode materials

Graphene and graphene composites are a major advance in anode materials for lithium-ion batteries. These materials are characterized by their higher specific capacity and enhanced safety features, making them a superior alternative to graphite. First, they exhibit a higher specific capacity, which directly contributes to increasing the energy density of the battery. Second, the special conductivity of these materials improves the charge and discharge rate, as well as the overall efficiency of the battery. In addition, their high chemical stability improves battery cycle life and safety. Finally, the tunability of graphene and graphene composites allows their structure and properties to be customized by adjusting the preparation conditions to meet the different needs of various applications.

Titanium oxide nanotubes are used as anode materials for lithium-ion batteries. These nanotubes have high specific surface area and abundant nanoporous structure, which provide more lithium storage locations and thus have higher specific capacity. In addition, their inherent chemical and structural stability contributes to enhanced cycle stability, allowing for extended battery life. In addition, titanium oxide nanotubes exhibit minimal volume expansion during the charge-discharge cycle compared to conventional silicon anodes. This feature reduces the mechanical stress in the battery and further increases the cycle life. The high chemical and thermal stability of titanium oxide nanotubes also improves the safety of lithium-ion batteries and reduces the possibility of thermal runaway. Taken together, these properties make titanium oxide nanotubes a promising alternative to traditional anode materials.

## 3.3 Breakthrough in electrolyte solutions

Ionic liquid gel electrolytes represent an innovative class of electrolyte materials, synthesizing the benefits of ionic liquids and polymer gels. These electrolytes are notable for their high ionic conductivity, mechanical stability, and chemical robustness. The preparation process involves dissolving ionic liquid and polymer to form a gel via cross-linking reactions, resulting in a material that boasts both high ionic conductivity and mechanical stability, making it suitable for use in electrochemical devices like lithium-ion batteries.

Compared to traditional liquid electrolytes, ionic liquid gel electrolytes offer several advantages. Their high ionic conductivity enhances the battery's power density, while their mechanical stability mitigates mechanical stress during cycling, thereby extending the battery's lifespan. Additionally, their chemical stability decreases the battery's cycle decay rate, further improving longevity. The low volatility of these electrolytes also diminishes the safety risks associated with battery operation.

In addition, solid electrolytes, emerging as a novel category of electrolyte materials, offer enhanced safety, a broader electrochemical window, and an extended cycle life compared to traditional liquid electrolytes. Comprising polymers, inorganic substances, or compounds, solid electrolytes are suitable for a variety of electrochemical devices, including lithium-ion batteries, sodium-ion batteries, and solid-state capacitors.

For example, in this research, the $AlCl_3$-GDNHCl electrolyte was prepared from guanidinium hydrochloride (GdnHCl) and anhydrous aluminum chloride ($AlCl_3$). Under the condition of heating and stirring, the solid quaternary ammonium analogs GdnHCl and $AlCl_3$ formed deep eutectic ionic liquid analogs containing $AlCl_4$ and $A_{2l}C_{l7}$ anions. An aluminum-graphite cell using $AlCl_3$-GDNHCl provides A discharge-specific capacity of about 125 $mAhg^{-1}$ at 1 $Ag^{-1}$ (whereas a conventional $AlCl_3$/EMIC provides only 60 mAh under the same conditions) $g^{-1}$) More than 1000 cycles of capacity retention rate of more than 90%, and provide nearly 99.5% high CE; Provides a discharge specific capacity of 128 mA $hg^{-1}$ at 100 $mAg^{-1}$ ($AlCl_3$/EMIC−84.7$mAhg^{-1}$),exhibiting excellent charge-discharge cycles and high capacity retention [3].

Solid electrolytes outperform liquid electrolytes in several key areas. Their lower volatility and higher melting point significantly reduce the safety risks associated with battery operation. The electrochemical window of the solid electrolyte allows for operation at higher voltages, thus increasing the energy density of the battery. In addition, their chemical and mechanical stability helps to reduce cycle decay rates and increase battery cycle life. As an important solid electrolyte material, garnet electrolyte has high ion conductivity and chemical stability, and can be used in lithium-ion batteries, sodium-ion batteries and other types of batteries. Compared with traditional liquid electrolytes, garnet-type electrolytes have higher electrochemical stability, lower combustion risk and longer life, so the safety and energy density of batteries can be greatly improved. One of the most notable SSE prospects is garnet-type LLZO SSEs, which have favorable ionic conductivity, a broad electrochemical window, and good compatibility with metallic lithium. [4].

# 4 Effect of nanotechnology on battery performance

## 4.1 Nano-engineering for enhanced interfaces

The nanostructure of the electrode surface can improve ion transport and cell efficiency by increasing the electrode surface area and shortening the ion transport path. Among them, 1D, 2D, and 3D nanostructures are commonly used electrode surface nanostructures.

One-dimensional nanostructures usually refer to materials with one-dimensional nanostructures, such as nanowires, nanotubes, etc. The nanostructure has a high specific surface area and fast ion transport rate, which can effectively improve the power density and cycle life of the battery. Recent studies have shown that electrospinning with one-dimensional nanostructures can effectively promote the efficient transport of ions and electrons when used as a substrate to support electrode materials, thereby improving the electrochemical properties of the materials [5].

Two-dimensional nanostructures usually refer to materials with two-dimensional nanostructures, such as graphene, molybdenum disulfide, etc. This nanostructure has high conductivity and high specific surface area, which can improve the power density and cycle life of the battery. In recent years, the application of two-dimensional chromium oxide nanosheets in lithium-ion batteries has been proposed. The electrode has A high capacity and stable cycle performance, when the charge and discharge rate is 0.2 g/A, the electrode capacity remains at 986 mAh/g after 297 cycles. At high magnification, stable circulation can still be achieved at high capacity. The excellent electrochemical performance of chromium oxide nanosheets is due to the stable stacking of two-dimensional structures, the short diffusion distance of electrons and ions, and the strong bonding ability between active substances and the collector fluid. The results show that the design of a two-dimensional structure can improve the electrochemical properties of oxide anode materials [6].

Three-dimensional nanostructures usually refer to materials with three-dimensional nanostructures, such as porous metals, porous carbon, etc. The nanostructure has a high specific surface area and fast ion transport rate, which can improve the power density and cycle life of the battery. In recent years, it has been proposed that flow-through 3D Flow porous anodes can improve fuel delivery and reduce fuel penetration, showing great potential for improving battery performance. Electrodes with a 3D structure can provide efficient active regions, as well as provide efficient electron and ion transport paths [7].

## 4.2 Nanocomposites for electrodes

The Carbon/conductive polymer composites can generally achieve excellent electrochemical properties. For example, in this research, For usage as supercapacitor electrodes, flexible polyaniline-carbon nanofiber (PANI-CNF) composites were created and assessed. Flexible carbon nanofibers were created using sol-gel and electrospinning processes, and an in-situ chemical polymerization process was used to coat the electrodes with polyaniline to enhance their electrochemical characteristics even more. Flexible PANI-CNF electrode performance in symmetric supercapacitor cells was studied.The results demonstrated that the flexible PANI-CNF electrodes without binder had a high capacitance of 234 F/g and good cycling stability, with 90% of the capacitance remaining after 1000 cycles. Ragone graphs were also displayed, and the flexible PANI-CNF electrode made with a 12-hour polymerization process attained a high energy density of 32 Wh/kg at a power density of 500 W/kg. Furthermore, mechanical testing revealed that PANI-CNF electrodes that were free-standing were durable and highly flexible [8].

Excellent electrochemical characteristics may generally be achieved by carbon metal-oxide composites. For instance, in this study, a well-dispersed porous $MnO_2$-carbon nanotube (CNT) composite was made for use as a supercapacitor electrode material. Rapid electron/ion transport kinetics were made possible in the electrode by the porous CNT network and the small $MnO_2$ nanoparticles. Even at a high current density of 20 $Ag^{-1}$ (128 mA $cm^{-2}$), the $MnO_2$-CNT composite showed an excellent areal capacitance of 1.0F $cm^{-2}$ at 0.2$Ag^{-1}$ (1.28 mA $cm^{-2}$). Its retention rate was 77%. This was accomplished on the electrode with a mass loading as high as 6.4 mg $cm^{-2}$. The electrode exhibited a high power density of 45.2 kW $kg^{-1}$ (0.29 W $cm^{-2}$) together with a decent energy density of 16.7 Wh $kg^{-1}$ (106 µWh $cm^{-2}$). Even after 3000 cycles of charging and discharging at 1 $Ag^{-1}$, it did not seem to fade. There is a lot of promise for using this porous, uniformly dispersed $MnO_2$-CNT combination in supercapacitors [9].

### 4.3 Nano-engineering for enhanced interfaces

Nanostructure safety characteristics are an important issue in battery research because batteries can overheat and cause safety problems during use. Experimental investigations were conducted on MWCNT, graphene-based, and MWCNT/Graphene-based composite phase change materials (PCM) to enhance the efficiency of the thermal management system for Li-ion power batteries. The findings indicate that, when compared to graphene-based PCM, MWCNT-based PCM, and pure PCM, the MWCNT/graphene mass ratio of 3/7 PCM composites exhibits the highest synergistic augmentation of heat transmission, with thermal conductivity increasing by 31.8%, 55.4%, and 124%, respectively. Furthermore, as compared to pure phase change materials, the temperature rise/fall rate of this composite material can be shortened by 63.3% and 50.0%. Lastly, a comparison between the temperature and phase transformation characteristics of pure PCM and MWCNT/graphene-based PCM was made. Composite phase change materials show great potential in the thermal management of lithium-ion power batteries [10].

## 5 Challenges

### 5.1 Design and manufacturing

The large-scale manufacturing of nanostructured batteries is a challenging problem. Due to the special properties of nanostructures, the manufacturing process requires high-precision machining and control techniques. At the same time, nanostructures are expensive to manufacture and require high-end equipment and materials. At the same time, the opportunity after the challenge is also obvious, large-scale manufacturing of nanostructured batteries can innovate the entire battery industry and benefit human society.

Further, designing batteries for aviation applications entails addressing several critical factors to meet the unique demands of aircraft, including energy density, safety, cycle life, temperature range, weight, and volume. High energy and power density are paramount for aviation batteries to satisfy the aircraft's need for high-energy storage and rapid charge-discharge capabilities. Safety is another crucial consideration; batteries must be designed to mitigate risks of fire or explosion, incorporating measures to prevent overcharging, over-discharging, overheating, and short-circuiting. Additionally, a long cycle life is essential to minimize the need for frequent battery replacements and maintenance, thereby reducing operational costs. Batteries must also operate reliably across a wide temperature range, enduring both high and low extremes encountered during flight. Furthermore, minimizing weight and volume is vital to reduce the aircraft's overall weight and enhance its payload capacity.

Given these diverse requirements, battery design for aviation is inherently a bespoke service. Different types of aviation machinery necessitate tailored battery solutions to fulfill specific operational tasks, underscoring the need for customized design approaches in this field.

### 5.2 Design and manufacturing

Integrating advanced batteries into aircraft systems is bound to be a lengthy process that involves countless details and steps as shown below:

1. Battery management system: The battery management system (BMS) is a key component of the integrated battery, which is responsible for monitoring the status of the battery, controlling the charge and discharge process, and protecting the battery from overload, over-discharge, and overheating. BMS needs to be integrated with the electrical and control systems of aircraft systems and meet aerospace industry specifications.
2. Power system: The battery needs to be integrated with the aircraft's power system to ensure that the battery can provide the required power and energy. The power supply system needs to consider parameters such as the battery's output voltage, current, and power, and ensure that the battery can switch seamlessly with other power systems.
3. Mechanical design: The battery needs to be integrated with the mechanical structure of the aircraft, including installation location, fixing method, and shock and vibration resistance design. The mechanical design needs to consider parameters such as the weight, volume and shape of the battery, and ensure the safety of the battery.
4. Thermal management: The charge and discharge process of the battery generates heat, and effective thermal management is required to ensure that the battery can operate within the specified temperature range. Thermal management needs to consider factors such as the way the battery dissipates heat, the cooling system, and temperature control.
5. Safety: The integration of batteries into aircraft systems needs to meet the safety specifications of the aerospace industry to ensure the safety of batteries. Safety considerations include the design of the battery to prevent fire, explosion and short circuit.

### 5.3 Environmental impact and sustainability

Life Cycle Analysis (LCA) of advanced battery materials is a comprehensive method used to evaluate the environmental impact and sustainability of these materials throughout their entire lifecycle, encompassing raw material acquisition, production, usage, and disposal. The acquisition of raw materials for battery production involves significant environmental considerations, including land use, water and energy consumption, and emissions of waste. LCA methodologies assess the sustainability and environmental footprint of these initial stages. During the production process, battery materials generate environmental impacts related to energy use, wastewater, exhaust emissions, and solid waste, necessitating a thorough evaluation of production sustainability. In the usage phase, the environmental impact is influenced by factors such as the battery's energy density, cycle life, and efficiency in charging and discharging. LCA examines these parameters to determine the operational efficiency and environmental consequences of battery materials. Finally, the disposal of battery materials introduces challenges related to waste management and pollutants. Effective LCA practices incorporate strategies for recycling and reusing battery materials to mitigate environmental impacts and enhance sustainability.

Overall, LCA provides a holistic framework for assessing the environmental impacts of battery materials across their lifecycle, guiding the development of more sustainable and environmentally friendly battery technologies.

In the aviation sector, battery recycling and reuse is an important strategy to improve the sustainability of battery materials. Due to the very high requirements for batteries in the aviation sector, the service life of batteries may be shorter, and the number of discarded batteries may be higher. If these waste batteries cannot be effectively recycled and reused, it will have a serious impact on the environment. The following are the methods proposed by the author for battery recycling and reuse: 1. Design recyclable batteries 2. Establish a recycling system 3. Promote the recycling and reuse technology of batteries 4. Strengthen battery material life cycle assessment.

For example, in recent research, Chen et al. [11] tested and analyzed the use of lithium-ion batteries without leaching treatment, selected lithium carbonate as lithium source and glucose as a carbon source for carbon coating, and finally used a solid-state sintering method to restore lithium-ion batteries. The crystal structure of the cathode material regained electrochemical activity, and the product exhibited electrochemical properties similar to those of commercial lithium iron phosphate lithium-ion batteries [12].

## 6 Conclusion

Advanced battery technology is not only the core technology of future electric aircraft, but also one of the key technologies of future power systems and electric vehicles. The high energy density of cash battery technology, long-lasting battery life, ultra-high battery safety, relatively low operating costs and the ability to achieve sustainable aviation will certainly make electric aircraft enter the historical stage. Bring aviation to the electric age.

In the previous content of this paper, the author mentioned a number of battery technologies, among which MWCNT/Graphene-based composite phase change material technology has excellent thermal management performance of batteries, porous $MnO_2$-carbon nanotube composite technology and flexible polyaniline carbon nanofiber composite technology has excellent charge-discharge cycle capability, and so on. Each battery technology has its own strengths, but it also has its own shortcomings. Through comparison, the authors found that porous $MnO_2$-carbon nanotube composite technology is very potential, which not only has excellent charge-discharge cycle capacity but also excellent high power density.This new material technology has great potential for practical applications.

While there are still many challenges to overcome, the authors believe that with enough investment, laboratories working together, innovating and not resting on their laud, the remaining challenges can be overcome and the vision of all-electric, sustainable aviation can be realized.

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