Review

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Review

A Review on Key Technologies and Developments of Hydrogen Fuel Cell Multi-Rotor Drones

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Abstract: Multi-rotor drones, a kind of unmanned equipment which is widely used in military, commercial consumption and other fields, has been developed very rapidly in recent years. However, their short flight time has hindered the expansion of their application range. This can be addressed by utilizing hydrogen fuel cells, which exhibit high energy density, strong adaptability to ambient temperature, and no pollution emissions, as the power source. Accordingly, the application of hydrogen fuel cells as the power source in multi-rotor drones is a promising technology that has attracted significant research attention. This paper summarizes the development process of hydrogen fuel cell multi-rotor drones and analyzes the key obstacles that need to be addressed for the further development of hydrogen fuel cell multi-rotor drones, including structural lightweight, hydrogen storage methods, energy management strategies. Additionally, prospects for the future development of hydrogen fuel cell multi-rotor drones are presented.

Keywords: hydrogen fuel cell; multi-rotor drone; lightweight design; hydrogen storage method; energy management strategy

1. Introduction

Depending on their structure, drones can be divided into three types: fixed-wing drones, single-rotor drones, and multi-rotor drones [1,2]. Compared to the other two types of drones, multi-rotor drones can take off and land vertically, hover in the same place for a long time [3], and exhibit a simple structure and strong maneuverability [4], making them very suitable for aerial photography [5,6], patrol inspection [7,8], pesticide spraying [9–12], and other types of missions in various fields, including commercial consumption or engineering applications. Accordingly, multi-rotor drones are currently the mainstream products in the drone market.

Despite their promising advantages, the short flight time of multi-rotor drones is one of the key factors limiting their further development [13]. Lithium batteries are used as the power source in most of the existing mature multi-rotor drones. However, the energy density of lithium batteries is 130–200 Wh/kg, whereas the power loading (the weight that can be lifted by unit power) of multi-rotor drones is typically approximately 10 g/W, which limits the battery weight that can be handled by the drone [14], making the flight time of multi-rotor drones powered by lithium battery very short (typically within 40 min) [15]. Therefore, battery replacement is required during the frequent start and stop operations of these drones. In contrast, the energy density of fuel cell systems is 250–540 Wh/kg [16], indicating that fuel cells can power at least twice the flight time that can be powered by lithium batteries at the same weight, making them very suitable for long-time flight [17]. This is of great significance for improving the endurance of multi-rotor drones, improving charging efficiency, and reducing the labor intensity of operators. Figure 1 shows a Ragone plot illustrating the energy density vs. power density of various power sources, and the plot indicates the significantly higher energy density of fuel cells compared to other power sources. In addition to the previously mentioned limitations of lithium batteries as the power source of drones, there are some other disadvantages

[18]: 1) lithium batteries easily short circuit or overcharge, making them unsuitable for long-term use; 2) lithium batteries experience a large temperature increase during operation, which may result in the burning of the drone if the temperature increases to a critical point; 3) easy detection by infrared detectors owing to the heat generated by the lithium battery during the flight of the drone, thus limiting the application of drones in the military field; 4) negative impact on the environment during the recycling process. In contrast, the service life of fuel cells is approximately three times that of lithium batteries [19] and fuel cells only discharge water during operation, making them superior to lithium batteries in terms of environmental impact. Consequently, drones powered by fuel cells have emerged as a hot technology being researched in various countries.

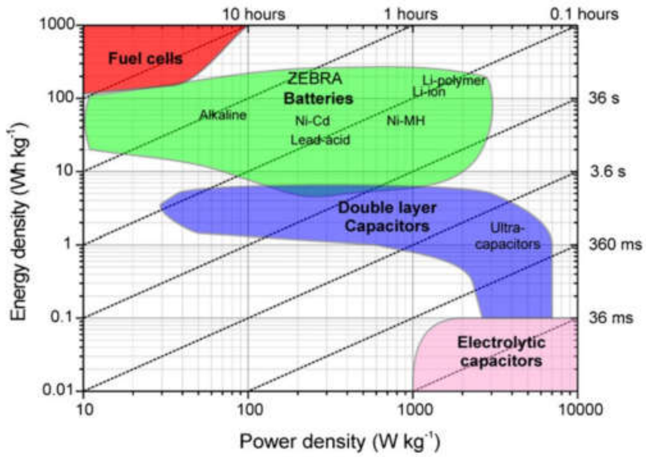

Figure 1. Ragone plot describing the energy density vs power density of various energy storage technologies [20].

The types of fuel cells commonly used in drones are proton exchange membrane fuel cells (PEMFC), direct methanol fuel cells (DMFC), and solid oxide fuel cells (SOFC). Among these, PEMFCs exhibit a light weight, high energy density, low operating temperature, and long service life, making them the most widely used fuel cells in drones [21].

As shown in Figure 2, a typical PEMFC structure is divided into a cathode flow channel, anode flow channel, gas diffusion layer, catalytic layer, and proton exchange membrane [22]. Hydrogen diffuses into the gas diffusion layer after passing through the anode flow channel, loses electrons under the action of the catalytic layer, and transfers protons to the cathode side through the proton exchange membrane. Oxygen diffuses into the gas diffusion layer after passing through the cathode channel, and combines with the protons passing through the proton exchange membrane and the electrons from the external circuit to form water under the influence of the catalyst. Through these reactions, a fuel cell can form a continuous current between the cathode and anode. Typically, the cathode and anode flow channels are designed on the front and back of the same conductive plate to form a bipolar plate [23], and the gas diffusion layer, the catalytic layer, and the proton exchange membrane are combined to form a membrane electrode [24]. This design enables the stacking and combination of the fuel cell stack in a “bipolar plate-membrane electrode-bipolar plate” configuration.

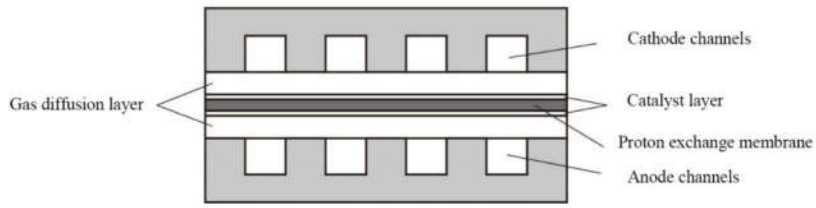

Figure 2. Proton exchange membrane fuel cells (PEMFC) single cell structure.

During operation, PEMFCs generate tremendous heat, which can result in the drying out of the membrane electrode and the subsequent deterioration of the performance of the cell if the heat is not discharged in time [25]. Consequently, a cooling system is an important part of fuel cells. Depending on the cooling methods, PEMFCs can be divided into water-cooled type and air-cooled type [26], Compared to water-cooled PEMFCs, air-cooled PEMFCs cool the stack via air purging without complicated auxiliary systems, making the entire system simpler and lighter. This is particularly advantageous in low-power devices, such as drones, which require less heat dissipation. Depending on their structure, air-cooled PEMFCs can be further subdivided into three types: area air-cooled [27], edge air-cooled [28,29], and open-cathode type [30]. In the open-cathode type, the cathode channel is exposed to the atmosphere, and the flowing air simultaneously provides the oxygen required for the cathode reaction and cools the stack through fan suction. This type of fuel cell combines the advantages of simple structure and large power range, making it the most widely used and advanced fuel cell among the three types of air-cooled PEMFCs.

In summary, the open-cathode PEMFC has the advantages of a high energy density, low noise, and no pollution, and is an ideal power source for multi-rotor drones. This paper presents the development history and technical status of hydrogen fuel cell multi-rotor drones, and analyzes the key technologies that need further research in the field of hydrogen fuel cell multi-rotor drones.

2. Development and Application of of hydrogen fuel cell multi-rotor drones

Air-cooled fuel cells are often used in small mobile devices, such as bicycles, forklifts, and drones. Among these devices, drones are not only the most technically difficult devices for fuel cell applications but also the devices that best demonstrate the superiority of fuel cells.

Research on hydrogen fuel cell multi-rotor drones just started in recent years. In 2015, EnergyOr, located in Montreal, Canada, developed H2Quad series drones powered by its EPOD fuel cell [31]. This drone can fly for 2 h with a load of 1 kg, and its effective flight radius is three times that of battery-powered multi-rotor drones [32]. Similarly, a British company, Intelligent Energy, tested DJI Matrice 100 drone equipped with its fuel cells in 2015, and observed that the flight time of the drone can reach up to 1 h. Additionally, in 2015, Singapore's Horizon Energy System (HES) launched Hycopter fuel cell drone for large-scale industrial maintenance and inspection [33]. This drone can fly for 3 h with a 12-L (3.5 kg) gas cylinder, and they implemented a highly lightweight design for each key component of its power system. Wuhan Zhongyu Power Co., Ltd. released a six-rotor drone "Ranger" equipped with its fuel cell system, HyLite1200, in 2015 [34]. The drone uses a 9 L/30 MPa high-pressure gas cylinder, and achieved a flight time of 3 h 30 min during the field test, setting a record for the flight time of drones at the time.

The world's first manufactured hydrogen fuel cell multi-rotor drone is HYDrone-1800 [35,36], which was released by MicroMultiCopter Aero Technology (MMC) in 2016. The fuselage of HYDrone-1800 is composed of carbon fiber materials and adopts a 6-axis design. It has a wheelbase of approximately 1.8 m, a maximum load of 25 kg, and a maximum flight radius of 100 km. The drone can fly continuously for 270 min with a 14-L gas cylinder and is suitable for inspection operations in various outdoor environments. In 2017, FlightWave developed a multi-rotor drone named Jupiter-H2 powered by Intelligent Energy's 650W fuel cell [37]. The Jupiter-H2 uses a narrow profile 70 cm

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fuselage and is equipped with 8 high thrust engines, and achieved a flight time of above 2 h. Some early hydrogen fuel cell multi-rotor drones are shown in Figure 3.

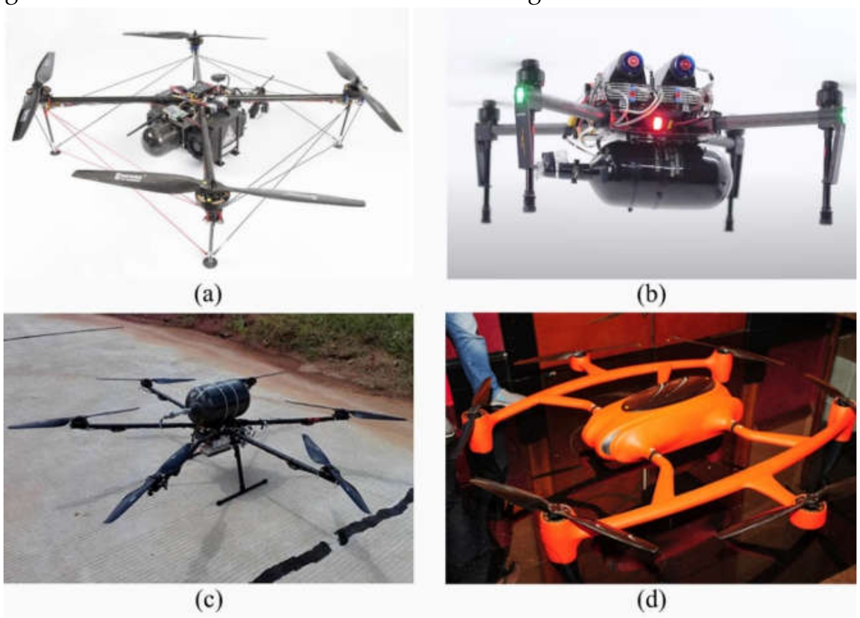

Figure 3. Early hydrogen fuel cell multi-rotor drones: (**a**) H2Quad from EnergyOr; (**b**) Fuel cell drone from Intelligent Energy; (**c**) Ranger from Zhongyu Power; (**d**) HYDrone-1800 from MMC.

Owing to its long flight time and good environmental protection, the application of fuel cell drones has been gradually promoted. In 2018, ISS Aerospace in the UK launched a drone named Sensus4 powered by Intelligent Energy's air-cooled fuel cell platform IE-Soar 800W [38], and also launched Sensus6 [39] powered by IE-Soar 2400W in 2019. These two drones are equipped with light gas cylinders produced by AMS, with payloads of 1.5 and 8 kg, respectively. The main application fields of these drones include the energy, environment, and military industries. In 2018, HES commercially released Hycopter [40], and the fuel cell system of this drone has an energy density of 700 Wh/kg and a power density of more than 1 W/g. Additionally, Hycopter uses a hydrogen regulator with a weight of only 140g, has a flight time of 3.5 h, and can carry high-speed precision cameras and various sensors for longer periods. In the same year, Skycorp, an Estonian drone manufacturing company, released a fuel cell quadcopter drone with AI functions——e-Drone Zero [41]. The drone was equipped with an Intelligent Energy's IE-Soar 800 W fuel cell and an AI operating system that can perform complex operations and provide security measures, such as obstacle avoidance based on machine vision. In 2019, the drone photography company, BATCAM, applied the fuel cells of Intelligent Energy to a multi-rotor drone [42], making the drone's flight time reach 70 min with a load of 5 kg, whereas the flight time of multi-rotor drones using lithium batteries from the same company is only 12 min. In 2020, Norway's Nordic Unmanned installed HES's 2000W air-cooled fuel cell system [43] on its Staaker BG-200 drone, and after a successful test flight, the company planned to further apply the drone to logistics, search, rescue, and inspection. Some fuel cell multi-rotor drones used for inspection are shown in Figure 4.

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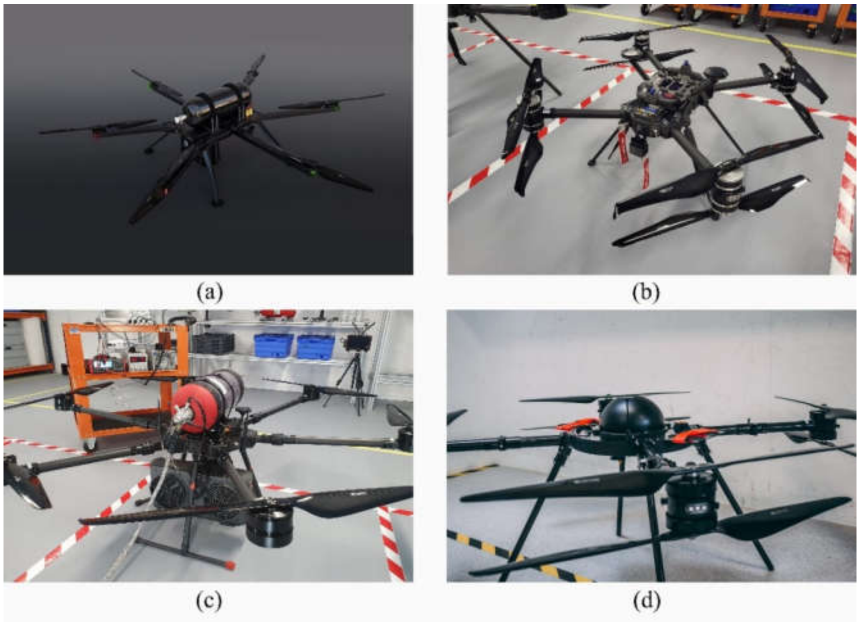

Figure 4. Hydrogen fuel cell multi-rotor drones for inspection: (**a**) Hycopter from HES; (**b**) Sensus4 from ISS Aerospace; (**c**) Sensus6 from ISS Aerospace; (**d**) Staaker BG-200 from Nordic Unmanned.

To further improve the flight time of fuel cell multi-rotor drones, researchers are attempting to increase the hydrogen carrying capacity of drones by changing the hydrogen storage method. Based on Intelligent Energy's IE-Soar 800W fuel cell in 2019, Meta Vista from South Korea equipped a drone with a 6 L liquid hydrogen tank as shown in Figure 5, increasing the energy density of the power source to 1865 Wh/kg, increasing the flight time of the drone beyond 12 h [44]. However, owing to the high cost of using liquid hydrogen, the difficulty of storage and the imperfection of related technologies, other drone companies have not attempted this technical route, and compressed gaseous hydrogen storage method is still the most widely used hydrogen storage method in multi-rotor drones.

Figure 5. The liquid hydrogen storage fuel cell drone from Meta Vista.

With the advancement of technology, fuel cells for drones are gradually being commercialized and serialized. Currently, the companies with the most in-depth and advanced research on fuel cell drones include the Intelligent Energy from the United Kingdom and Doosan Mobility Innovation (DMI) from South Korea, and both companies can independently develop air-cooled fuel cell stacks and power systems for drones. The common features of drones manufactured by these companies include high integration and modularization. Intelligent Energy's IE-Soar series of fuel cells for

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drones are currently one of the lightest fuel cell modules in the world, and this company has achieved a high stack power density exceeding 800 W/kg, including IE-Soar 650W [45], IE-Soar 800W [46] and IE-Soar 2400W [47]. These modules can increase the weight and space that the auxiliary equipment can occupy, thereby prolonging the flight time of the drone. Figure 6 shows an IE-Soar 650W fuel cell module and a drone powered by the IE-Soar 650W. To enhance the series connection of fuel cell stacks, Intelligent Energy has developed a power path module (PPM) [48,49] adapted to IE-Soar 650W and IE-Soar 800W. This module can simultaneously distribute hydrogen and transfer energy, and combine various fuel cell power modules (FCPM) in different ways, and this plays a very important role in expanding the power range of drones. Based on the PPM module, Zepher from the United States used two IE-Soar 800W fuel cells on the vertical take-off and landing drone of the US Army [50].

Figure 6. IE-Soar 650W fuel cell module and the fuel cell drone developed based on IE-Soar 650W module.

The most significant feature of the products of DMI is the high integration. The components of the entire fuel cell systems manufactured by this company, including the gas cylinder and the auxiliary power source, are integrated in the same pack, allowing users to easily match the drones they need. Representative fuel cell packs of DMI include DP20 [51], DP30 [52] and DM30 [53]. The DP30 has a power of 2600 W and is considered the world's largest power fuel cell power pack module. The DM30 is the module removing housing from DP30. Additionally, DMI has developed ultra-light bipolar plates and a special stack structure for drones with a highly lightweight fuel cell pack, while ensuring the durability of the fuel cell and the uniformity of the output performance of the battery. As shown in Figure 7, the overall weight of DP30, consisting of a 10.8-L cylinder, is only 12 kg. Based on its own fuel cell pack, DMI has successively developed a series of drones, such as DT20, DS30 and DT30 [54]. Two DP30 modules have been combined to produce a 5.2 kW hydrogen fuel cell system, which was used to power a 39 kg medium-sized hexacopter, and the flight test results proved the feasibility of the 5.2 kW fuel cell system medium-sized hexacopter to perform stable flights. Currently, DMI's innovative drones have been applied in many fields, such as sea rescue, wind power inspection, road surface inspection, pipeline inspection, and logistics distribution [55].

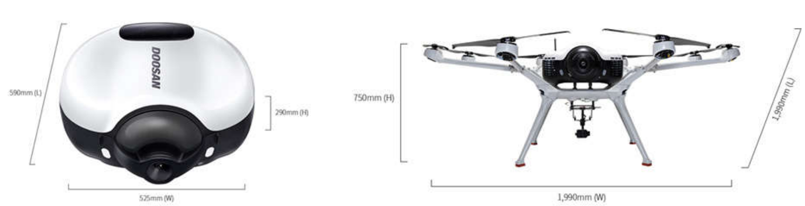

Figure 7. DP30 fuel cell pack and DS30 drone from Doosan Mobility Innovation.

Ballard launched FCair-600 and FCair-1200, two fuel cell systems for drones (Figure 8) [56]. These FCair series fuel cell systems utilize water-cooled fuel cell stacks, which significantly increases

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the overall weight of the system compared to that of air-cooled fuel cell systems of the same power, therefore, water-cooled fuel cell stacks have not been widely used in multi-rotor drones.

Figure 8. Fuel cell drone from Ballard.

China is the largest producer and consumer of hydrogen fuel cell drones in the world at present. As shown in Figure 9, in 2022, a total of 659 hydrogen fuel cell drones were produced globally, of which China accounted for 27.2%, and a total of 639 hydrogen fuel cell drones were sold, of which China accounted for 27.6%. Many Chinese companies have advanced manufacturing technology for hydrogen fuel cell drones. Beijing Xinyan Chuangneng Technology Co, Ltd. from China launched a six-rotor hydrogen fuel cell drone. The drone can fly continuously for 331 min with a 19 L/35 MPa light gas cylinder, setting a record for the flight time of a fuel cell drone based on a compressed gaseous hydrogen storage method [57]. Additionally, the drone also demonstrated that China is at the forefront of hydrogen fuel cell fabrication in the world. Zhejiang Hydrogen Aviation Technology Co., Ltd., another hydrogen drone company from China, developed Hercules ACFC-48-1700 and Hercules ACFC-48-2700 air-cooled stacks specially for drones. The stacks utilize carbon nano-microporous stacking technology, and exhibits a power density of approximately 700 W/kg. This same company manufactured Hydrocopter-04 drone, which is based on two 1250 W air-cooled stacks. This drone can fly for up to 4.5 h without load, and has been tested in various fields. With the continuous advancement in hydrogen energy drone technology, China launched the national standard "Hydrogen Fuel Cell Power System for Unmanned Aerial Vehicles" in June 2020 [58], which is the world's first national hydrogen fuel cell standard for drones.

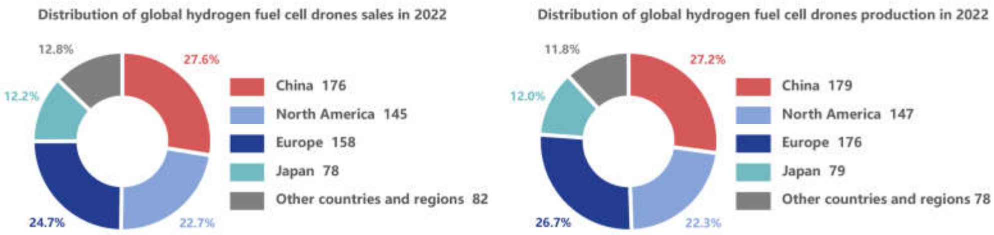

Figure 9. Global sales and production distribution of fuel cell drones in 2022, By regions.

3. Research status of key technologies

3.1. Lightweight design

Limited by the power loading of the propeller, when the power of the drone is constant, the total take-off weight of the drone is limited [59], thus necessitating a reasonable weight distribution of each hardware in a drone. The flight time of fuel cell drones mainly depends on the amount of hydrogen carried by the drone, that is, if the weight of each hardware can be reduced, the capacity of the gas cylinder can be increased to carry more hydrogen. Thus, the lightweight design of hydrogen fuel cell system hardware and the drone structure are important technical routes to improve the flight time of hydrogen fuel cell drones.

3.1.1. Bipolar plates

The main hardware of hydrogen fuel cell multi-rotor drones include fuel cell stacks, hydrogen cylinders, regulators, and fuselages. The key components of the fuel cell stacks are bipolar plates, which account for more than 80% of the entire weight of the fuel cells [60], so the lightweight design of bipolar plates is the key to realizing the lightweight of fuel cell systems. To reduce the weight of the bipolar plate, its materials need to be optimized. Common bipolar plate materials include graphite materials, metal materials, and composite materials [61].

Graphite materials have long been used in the manufacture of bipolar plates [62]owing to their low density, good corrosion resistance, and good affinity with carbon fiber diffusion layers [63]. However, owing to their low strength and strong brittleness, graphite bipolar plates are typically fabricated with a high thickness to meet the strength requirements of the stack, resulting in the large volume and mass of the stack. Although some scholars have reduced the thickness of bipolar plates by improving the structure of graphite plates [64,65], graphite materials are still inferior to the other two materials in terms of lightweight design.

Composite bipolar plates are bipolar plates fabricated by the injection molding of a polymer resin with conductive fillers, such as graphite [66–68]. The specific strength of composite bipolar plates is higher than that of graphite bipolar plates, thus they exhibit significant advantages in terms of lightweight design, but owing to their complicated manufacturing process and high cost, composite bipolar plates are currently not widely used. With the development of 3D printing, researchers are attempting to adapt this technology to simplify the manufacturing process of composite bipolar plates. For example, a previous study [69] developed and fabricated a lightweight stack based on the Horizon 100W fuel cell stack. The bipolar plates of the stack were fabricated with PETG material using 3D printing technology, and the bipolar plates were endowed with conductivity because PETG is an electrically insulative material. The results revealed that through the redesign of materials and processes of key components, such as bipolar plates, the total weight of the original 100W fuel cell stack was reduced from 384 to 170 g, and the maximum estimated power density of the redesigned fuel cell stack was very close to that of Horizon fuel cell stack.

Metal materials exhibit good electrical conductivity and processability, and can be directly formed by stamping, so they are currently the most widely used bipolar plate materials [70]. Through comparative studies, Hung et al. [71] reported that metal bipolar plates can save at least 12% of hydrogen consumption compared to graphite composite bipolar plates under the same working conditions (Figure 10). According to related reports, South Korea's DMI and POSCO SPS have developed 50 μm stainless steel bipolar plates for drone fuel cells [72], whose thickness is only half the thickness of the vehicle fuel cell bipolar plates and can effectively reduce the weight of drones. These two companies have now signed a memorandum of understanding to manufacture 20 μm ultra-thin bipolar plates.

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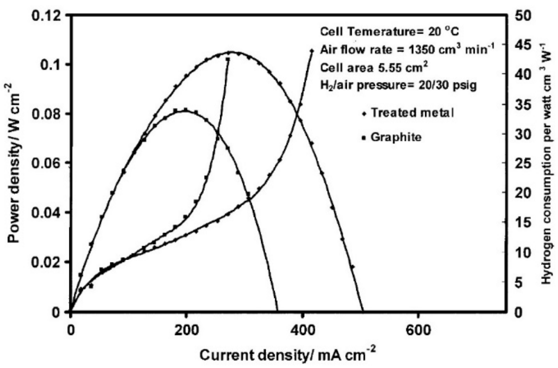

Figure 10. Power density and hydrogen consumption vs. current density [71].

Metal materials commonly used in the manufacture of bipolar plates include stainless steel [73], aluminum alloy [74], magnesium alloy [75], and titanium alloy [76]. From the perspective of lightweight design, lightweight alloys, such as titanium alloys and aluminum alloys, exhibit a low density compared to stainless steel. Additionally, compared to aluminum alloys and magnesium alloys, titanium alloys exhibit a higher specific strength and stronger corrosion resistance, and the corrosion products produced by titanium alloys during long-term use exert slight toxicity on the proton exchange membrane [77], making them ideal lightweight materials for bipolar plates. However, similar to other metal bipolar plates, a passivation film is formed on the surface of titanium alloy bipolar plates after long-term use, increasing the resistivity of the bipolar plate and reducing the output power of the fuel cell [78]. To avoid this phenomenon, it is necessary to modify the surface of the bipolar plate. Depending on the materials, surface modification methods mainly include carbon surface modification [79], chromium and chromium compound surface modification [80], nitride modification [81,82], and precious metal modification [83]. A previous study [84] reviewed the latest developments among popular coatings from the perspective of corrosion resistance, conductivity, and contact angle of metal bipolar plates in PEMFC environments, and also compared various metal bipolar plates materials and surface modification methods, among the studies cited in the review, Xie et al. [85]prepared a composite coating composed of carbon, polytetrafluoroethylene (PTFE), and TiN on Ti bipolar plates using the hydrothermal and impregnation method. They observed that the corrosion current density of the surface modified Ti bipolar plates was only 0.009 μA/cm2, which is lower than that of all the other modified bipolar plates. Additionally, the modified Ti bipolar plates also exhibit a very low interface contact resistance, indicating that the modified Ti bipolar plates can achieve excellent corrosion resistance and conductivity. However, owing to the high costs of titanium bipolar plates, they are rarely investigated and applied, making stainless steel the mainstream material for metal bipolar plates. In summary, to achieve fuel cell stacks with a lightweight design of from the perspective of substrate materials of metal bipolar plates, the rational use of modified materials and modification process to improve the corrosion resistance and conductivity of metal bipolar plates and the reduction of the costs of bipolar plates are the key issues that need to be addressed.

3.1.2. High-pressure gas cylinders and hydrogen regulators

Compressed gaseous hydrogen storage is currently the most widely used hydrogen storage method for mobile devices [86], and its carrier are high-pressure gas cylinders. Depending on the material and structure of the gas cylinder, high-pressure hydrogen gas cylinders can be divided into four types (type I, II, III, and IV) [87], which are listed in Table 1:

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Table 1. Technical parameters of the different types of high-pressure hydrogen cylinders [87]

Cylinder types	Materials	Hydrogen storage pressure (Mpa)	Mass percent (%)	Volumetric hydrogen storage density (g/L)	Service life (a)
Type I	All metal	17.5–20	≈1	14.28–17.28	15
Type II	Metal liner with hoop wrapping	26.3–30	≈1.5	14.28–17.28	15
Type III	Metal liner with full composite wrapping	30–70	2.4-4.1	35–40	15–20
Type IV	Plastic liner with full composite wrapping	>70	2.5-5.7	38–40	15–20

Among the four types of gas cylinders, Type I cylinders adopt an all-metal structure, whereas Type II, Type III and Type IV cylinders exhibit a fiber-wrapping structure (Figure 11). The purpose of adopting the fiber-wrapping structure is to apply a certain prestress to the liner by the tension of the fiber, thus improving the carrying capacity of the hydrogen cylinder. As the density of light fiber is significantly smaller than that of the liner, the weight of a fiber-wrapping gas cylinder is significantly smaller than that of an all-metal gas cylinder with the same hydrogen storage pressure and storage capacity [88]. The mass percent is the mass of hydrogen that can be loaded per unit mass of the cylinder. As Type II cylinders use metal liners, their mass percent is only slightly higher than that of Type I cylinders, which does not significantly reflect the lightweight advantages of fiber-wrapping cylinders. Type III and Type IV cylinders are the mainstream lightweight gas cylinders [89], using aluminum alloy and composite material liners, respectively, and their mass percent is 2.4–4.1 and 2.5–5.7, respectively.

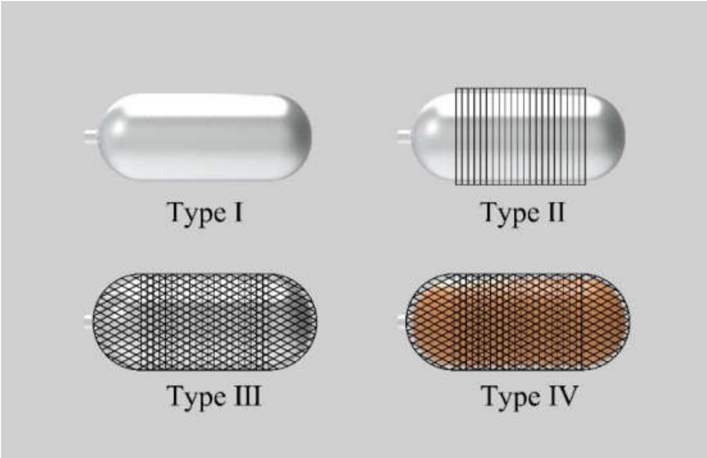

Figure 11. Structure of different types of gas cylinders.

Rohit et al. [90] fabricated Type I, Type II, and Type IV cylinders with a lightweight design using titanium, ABS, and carbon fiber, and performed deformation, impact, and drop tests on the various types of hydrogen cylinders. They observed that Type IV cylinders exhibited better overall properties and are 39.2% lighter than Type I cylinders, indicating the suitability of Type IV cylinders for hydrogen fuel cell drones. Cho et al. [91,92] developed a Type IV cylinder based on PET material for drones. The mass percent of the cylinder was 4.8%, and it exhibited good heat resistance and sealing. Currently, many companies have mastered advanced manufacturing technology for Type IV cylinders, and DMI (DMI), Hexagen Purus, and Composite Technical Systems all have serialized Type IV cylinders products.

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In addition to improving the materials of hydrogen cylinders, many scholars have attempted to achieve a lightweight design by optimizing the structure. Roh [93] added a doily structure to the cross-section dome of Type IV cylinders, which reduced the weight of the composite material used in Type IV cylinders by approximately 10%. Based on finite element analysis, Alcantar [94] used genetic algorithm and simulated annealing method to achieve a lightweight design for Type IV cylinders. The comparison of this method to that performed by Roh [93] indicated that the two methods reduced the weight of Type IV cylinders by 9.8 and 11.2%, respectively. Lee et al. [95] optimized the winding layer and winding angle of Type IV cylinders based on the genetic algorithm, and this reduced the weight of hydrogen cylinders by 23.79%, thus increasing the hovering time of a quadrotor drone with a 650 W fuel cell by 17.73%, which is 37.85% longer than the hovering time of the battery-powered drone with the same power.

The hydrogen regulator was installed on a high-pressure hydrogen cylinder through screw threads, which played the role of inflation, switch and decompression, which is a type of combination valve [96]. As one of the most important components of the hydrogen fuel cell system, research on lightweight hydrogen regulators is also very important for the lightweight design of the whole system. The main manufacturers of hydrogen regulators for drones include GFI, Pressure-Tech, HES, and Meyer. These companies have conducted tremendous research on the lightweight design of hydrogen regulators in terms of materials and structures and have formed their own product lines.

For instance, the Pressure-Tech's LW351 hydrogen regulator [97] is a type of hydrogen regulator used in the fuel cell drones of many companies. Its main features are miniaturization, integration, and lightweight, and it is made of AW6082 aluminum alloy with a minimum total weight of only 200 g that can reduce high pressure hydrogen from 35 to 0.3 MPa.

3.2. Hydrogen storage methods

Currently, there are three main hydrogen storage methods: compressed gaseous hydrogen storage, liquid hydrogen storage, and solid-state hydrogen storage [98].

3.2.1. Compressed gaseous hydrogen storage methods

Compressed gaseous hydrogen storage refers to the storage of hydrogen in gas cylinders at high pressure. The key to this technology lies in the structural strength and durability of high-pressure gas cylinders. Among the four types of existing gas cylinders, Type III and Type IV cylinders exhibit strong carrying capacity while achieving a lightweight. Type III cylinders use aluminum alloy liners, and Type IV cylinders use composite material liners with a higher mass percent. As the takeoff weight of multi-rotor drones is limited by the thrust of the motors, Type IV cylinders are more suitable for hydrogen storage on drones. In addition, to ensure the durability of gas cylinders, research on the anti-hydrogen embrittlement [99,100] and corrosion resistance of gas cylinder materials are key issues that need to be solved for high-pressure gas cylinders.

Owing to its simple operation, less energy consumption in the early stage, and low technical threshold, compressed gaseous storage method is the most widely used hydrogen storage method in the industry [101].

3.2.2. Liquid hydrogen storage methods

Liquid hydrogen storage should be capable of cooling hydrogen below -253 °C and store it in special containers in liquid form, and the hydrogen storage density can reach 70.8g/L [102] owing to the significantly higher weight of liquid hydrogen compared to gaseous hydrogen with the same volume. However, the use of liquid hydrogen storage technology can significantly improve the flight time of hydrogen fuel cell drones.

Stroman et al. [103] developed a liquid hydrogen storage system for drones using a dewar with autonomous pressure control function. After flight tests on a drone, they observed that the system could provide 85% more flight time than the compressed gaseous hydrogen storage system of the same weight. However, the large amount of energy required to liquefy the hydrogen and the special

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low-temperature heat-insulated container required by this technology result in high energy loss and high cost. This indicates that from a long-term and economic perspective, liquid hydrogen storage method is not suitable for multi-rotor drones that require frequent operations [104].

3.2.3. Solid-state hydrogen storage methods

There are two methods used to store hydrogen in solid state: one is the physical combination of hydrogen with hydrogen storage materials in the form of molecules, and the other is the chemical combination of hydrogen with other components through ionic bonds or covalent bonds to form hydrides [105]. Compared to the other two hydrogen storage methods, solid-state hydrogen storage method exhibits higher mass hydrogen storage density and is safer to use. The key to this technology is to realize the adsorption and release of hydrogen in hydrogen storage materials, so the research on solid-state hydrogen storage technology has focused on the physical and chemical properties of hydrogen storage materials [106].

Commonly used physical hydrogen storage materials mainly include carbon-based materials [107], silicon-based materials [108,109], metal framework materials [110] and other porous materials with large specific surface area. Hydrogen molecules combine with these materials through van der Waals force [111]. Chemical hydrogen storage materials mainly include metal-based alloy materials and coordination hydride materials [112]. In 2016, Scottish Association for Marine Science (SAMS) successfully tested a solid-state hydrogen storage fuel cell drone based on a chemical hydrogen storage material developed by Cella Energy [113]. Additionally, Korean scholars proposed a hydrogen generator based on NaBH4 as chemical hydrogen storage material for drones [114,115]. They observed that the gravimetric and volumetric specific energy densities of the hydrogen generator were 739.1 Wh/kg and 272.8 Wh/L, respectively, and the hydrogen consumption curve indicated the consistent hydrogen generation rate of the generator. Although the solid-state hydrogen storage method is still in the laboratory research stage, with the continuous advancement of this technology, solid-state hydrogen storage is bound to become an advanced, safe and highly efficient hydrogen storage method [116], which is of great significance for promoting the development of hydrogen fuel cell multi-rotor drones.

Different types of hydrogen storage methods are compared in Table 2.

Table 2. Comparison of various direct H_2 storage systems [117]

Storage System	**Mass Storage Efficiency (%kg H_2/kg storage)**	**Volumetric Storage Density (kg H_2/L storage)**	**Gravimetric Storage Energy Density (kWh/kg)**	**Volumetric Storage Energy Density (kWh/L)**
Compressed H_2, 300bars	3.1	0.014	1.2	0.55
Compressed H_2, 700bars	4.8	0.033	1.9	1.30
Cryogenic Liquid H_2	14.2	0.043	5.57	1.68
Cryo-compression tank (LLNL)	7.38	0.045	2.46	1.51
Metal hydride (conservative)	0.65	0.028	0.26	1.12

*Note: The mass and volume of the entire storage system (tank, valves, tubing, and regulators) are taken into account in these data.

3.3. Energy management strategy

Although hydrogen fuel cells exhibit a high energy density, no environmental impact, and low noise, they exhibit a slow power response, making them unsuitable for missions that require large

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instantaneous power [118]. In contrast, fuel cells are more suitable for missions requiring long-term discharge. Lithium batteries exhibit high-power discharge, so using a hybrid power system that combines hydrogen fuel cells and lithium batteries is an effective technical route to solve the shortcomings of hydrogen fuel cells [119,120].

Many scholars have demonstrated the superiority of the fuel cell–lithium battery hybrid power system. For instance, Ustolin [121] implemented a simulation model to analyze the energy and power demand according to the flight profile, and then compared a fuel cell–lithium battery hybrid power system and a lithium battery power system with the same weight, considering a 7 kg MTOW quadcopter drone with a 120 min flight profile. The results indicated that the fuel cell–lithium battery hybrid power system can provide significantly longer flight time than the lithium battery power system. Apeland [122] proposed a model for analyzing and quantifying the use of a hybrid fuel cell system on a multirotor drone. The model was applied to Staaker BG200 from Nordic Unmanned, an X8 multirotor drone with a maximum take-off mass of 25 kg. The results indicated that when multirotor drones and their energy source reaches a certain size and mass, fuel cell hybrid systems provide a longer flight time than LiPo-batteries, and as the weight of the energy system increases, the advantage of the hybrid system in terms of flight time becomes increasingly significant. Therefore, fuel cell–lithium battery hybrid power systems are typically utilized in advanced fuel cell drones.

A typical fuel cell–lithium battery hybrid system topology is shown in Figure 12. The fuel cell was connected in parallel with the lithium battery through a DC/DC boost converter, and then connected to the dynamic load. Additionally, to effectively manage the charging/discharging current of the battery, a bidirectional DC/DC converter was integrated between the battery and the DC bus, the control system distributes energy between the fuel cell and the lithium battery by adjusting the parameters of the DC/DC converters.

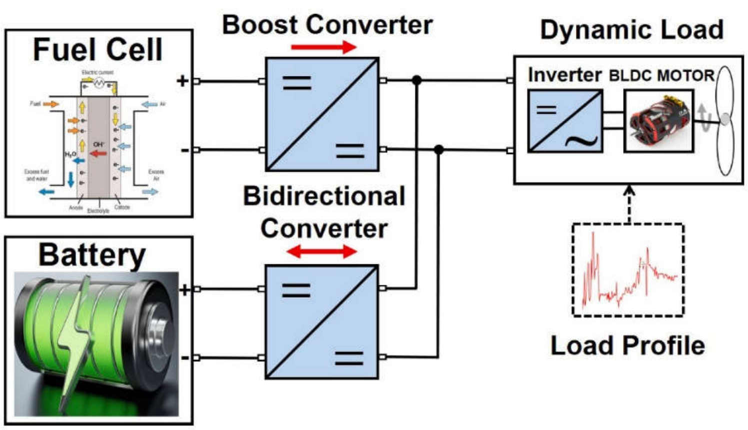

Figure 12. Hybrid power supply system topology [130].

There are typically three working conditions for multi-rotor drones: take-off or rapid climb (the power required by the drone is higher than the power of the fuel cell), cruise (the power required by the drone is equal to the power of the fuel cell), and landing (the power required by the drone is lower than the power of the fuel cell). When the control system recognizes the specific working conditions, it will control the battery to charge or discharge. According to the power demand, if the power required by the drone is higher than the power of the fuel cell, both the fuel cell and the battery are used; if the power required by the drone is lower than the power of the fuel cell, only the fuel cell is used; and if the SOC of the battery is less than 100%, the fuel cell will recharge the battery [123].

Energy management strategies (EMS) function to decide when to use hydrogen fuel cells and lithium batteries depending on the mission. Reasonable energy management strategies can effectively reduce unnecessary loss of hydrogen and improve the flight time of the drone. Thus, many scholars have conducted in-depth research on the energy management strategies of the hybrid power

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system for hydrogen fuel cell drones using different algorithms [124,125]. Traditional energy management strategies can be categorized into rule-based and optimization-based strategies. The rule-based strategy can be divided into deterministic strategy and fuzzy logic control strategy, and the optimization-based control strategy can be divided into global and real-time methods, which include dynamic programming (DP), equivalent consumption minimum strategy (ECMS), Pontryagin's minimization principle (PMP), and model predictive control (MPC). In addition to the two aforementioned types of strategies, to solve the dilemma of balancing precision and computation burden in optimization-based strategies, intelligent-based energy management strategies, such as neural network, genetic algorithm, and reinforcement learning [126] have attracted the interest of many scholars. An overview of fuel cell drones EMS is shown in Figure 13.

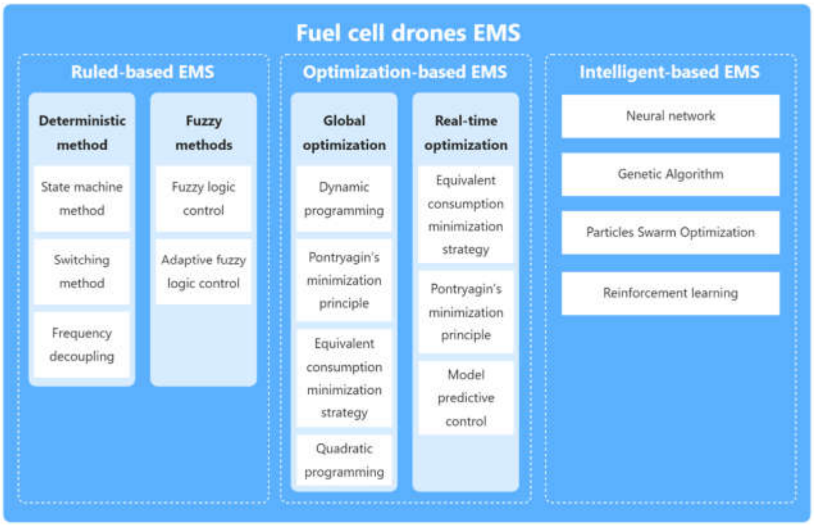

Figure 13. Overview of the energy management strategies of fuel cell drones [126].

Many of the aforementioned energy management strategies are designed for fixed-wing drones; however, compared to fixed-wing drones, multi-rotor drones exhibit higher power demand and more dynamic load profile. Thus, fuel cells must have a higher nominal power, a more active hybrid power management system, and a larger battery component, making the power system of multi-rotor drones heavier and more complex [127]. Therefore, this review mainly introduces some latest energy management strategies that have been applied to multi-rotor drones, which are discussed below.

Zhang [128] proposed an online fuzzy energy management strategy for the hybrid power system of fuel cell drones. The strategy was demonstrated to be capable of responding to instantaneous high-power demand, which is even twice the maximum power level of the fuel cell. Meanwhile, for different types of missions, the proposed online fuzzy energy management strategy uses the most power from the battery and consumes the least amount of hydrogen compared to the passive strategy and the state machine strategy. The hydrogen consumption of drones with different energy management strategies for different missions is shown in Figure 14.

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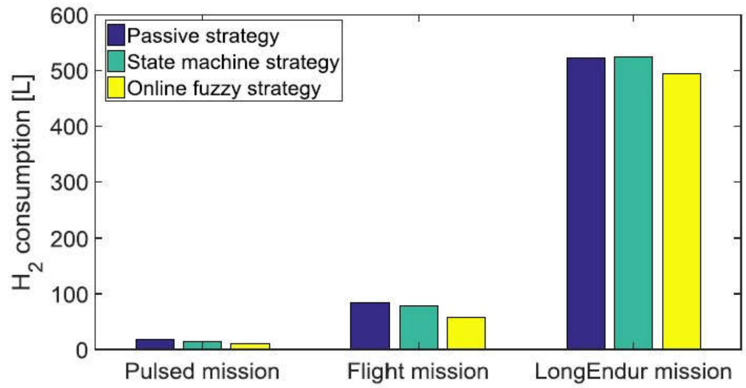

Figure 14. Comparison of the hydrogen consumption of drones based on the energy management strategies [128].

Lei et al. [129] compared several types of energy management strategies, including rule-based state machine strategy, fuzzy logic strategy, DP strategy, and equivalent consumption minimization strategy (ECMS). They observed that the four energy management strategies can all be optimized for a specific mission, and the same optimization effect cannot be achieved after the mission changes. Multi-rotor drones often need to deal with uncertain loads when performing different missions; therefore, an energy management strategy that can achieve good optimization results under different missions is more suitable for multi-rotor drones. Thus, based on simulations and test, the authors proposed the dynamic balance management energy strategy, and confirmed the high system efficiency of the strategy, as well as its ability to properly balance the energy consumption rate of the lithium battery and the fuel cell, avoiding a situation where one of the power sources is exhausted first.

Boukoberine [130] proposed a frequency separation rule-based energy management strategy (FSRB-EMS) and an ECMS based on the actual power consumption data of a six-rotor drone. They observed that FSRB-EMS improves the maneuverability of drones through fast power response, while also improving the efficiency and performance of the hybrid power system. In addition, the application of ECMS can improve the efficiency of hydrogen use and reduce the cost of fuel cell drones. This strategy is expected to save 3% of hydrogen, thus improving the record for longest flight time of fuel cell drones set by Meta Vista by 21.81 minutes. Furthermore, Boukoberine [131] optimized ECMS using multi-objective genetic algorithm, and the improved strategy is expected to save 5% of hydrogen, thus improving the record for the longest flight time of fuel cell drones set by Meta Vista by 37 minutes.

Liu [132] proposed an energy management strategy based on online DP and hierarchical model predictive control（HMPC). The simulation results revealed that compared to common energy management strategies, DP and hierarchical MPC can increase the flight time of fuel cell drones by 2.69 and 1.27%, respectively.

Yao et al. [133] proposed a HMPC energy management strategy based on grey Markov prediction. The model structure was divided into the trajectory optimization layer and the control layer. The trajectory optimization layer considers the economic cost of the drone to optimize the battery SOC reference trajectory. The control layer is a model predictive control, whose function is to follow the reference trajectory to obtain the optimal fuel cell output power. The author predicted the power demand of the drone using a grey Markov model, and reported that compared to fuzzy logic and ECMS, HMPC can save 3.78 and 3.57% of hydrogen consumption, respectively. Additionally, its performance is very close to that of Prescient MPC, indicating that the predictive model has a positive impact on the flight time of multi-rotor drones.

Yan et al. [134] proposed an adaptive real-time estimation method based on Kalman filter for tracking the maximum power point (MPP) of a hydrogen fuel cell in the hybrid power systems of drones. Simulation and experimental results demonstrated the enhanced effectiveness and accuracy of the proposed adaptive method than perturb and observe (P&O) and particle swarm optimization (PSO) methods. Additionally, under the inaccurate measurement condition, the adaptive method reduced the percentage of the maximum tracking error (MTE) of the operating power by 1.10 and 2.83%, compared to the PSO method and the P&O method, respectively. In addition, the convergence speed of the adaptive method is 33 and 65% faster than PSO and P&O method, respectively, indicating that the adaptive method can effectively reduce the oscillation of hydrogen fuel cells in hybrid power systems of drones.

Zeng et al. [135] designed a hydrogen fuel cell powered quadrotor based on a 3 kW PEMFC stack as a hybrid power system of drones. The proposed novel rule-based EMS framework based on online identification. The maximum power point (MPP) and the maximum efficiency point (MEP) could be extracted from the power and efficiency curves once the parameters of the fuel cell are updated owing to the shifts of the operating condition; thus, the EMS could track the real-time optimal points of the fuel cell and distribute the power precisely. Through flight tests and simulations, the strategy was proved to minimize the efficiency loss, prevent frequent charging from the fuel cell, thereby improving hydrogen economy and enabling persistent flight missions.

4. Summary and Future Scope

With the advancement of technology, hydrogen fuel cell multi-rotor drones have gradually moved towards industrialization and modularization. Many fuel cell companies have developed their own series of multi-rotor drones; however, hydrogen fuel cell multi-rotor drones are still in the exploratory stage and have not yet been fully recognized by the market. Moreover, their high cost problem is yet to be resolved. To further improve the performance of multi-rotor drones and expand their application range, in-depth research in basic science, engineering design, and top-level planning is still required. This paper summarizes some technical directions that fuel cell multi-rotor drone should focus on in the future：

1. Optimization of hydrogen storage methods;

Long flight time is the biggest advantage of hydrogen fuel cells as the power source of multi-rotor drones. To further exploit this advantage, future research should focus on lightweight design, hydrogen storage methods, and energy management strategies. Among these, optimizing hydrogen storage methods is the technical route that can most significantly improve the drone's flight time. Particularly, if efficient solid-state hydrogen storage can be achieved at a low cost, hydrogen fuel cell multi-rotor drones can truly achieve long-term and long-distance flight, and the drone industry will also usher in a revolutionary change.

2. Cathode gas filtration system;

As the cathode of the open-cathode air-cooled fuel cell is directly connected to the atmosphere, if the working environment is heavily polluted, the pollutants in the air will directly damage the membrane electrode. This will result in a decrease in the life of the fuel cell, hindering the use of hydrogen fuel cell drones in the polluted environments, such as coal mines and chemical plants. To expand the application scenarios of hydrogen fuel cell drones, further research on the cathode gas filtration system is needed.

3. Auxiliary equipment.

To achieve the large-scale application of hydrogen fuel cell drones, in addition to the drone equipment itself, it is necessary to systematically plan and design a complete set of technologies for hydrogen storage, hydrogen transportation, and hydrogenation. Compared to hydrogen fuel cell vehicles, multi-rotor drones utilize very little hydrogen, so a portable mobile hydrogen refueling process can be designed for them to meet the frequent use.

The research and development of hydrogen fuel cell multi-rotor drones is a systematic project that integrates new energy, robotics, energy management, and many other technologies. Its development is closely related to the progress of basic disciplines such as materials, chemistry, and thermodynamics, indicating that if hydrogen fuel cell multi-rotor drones are properly applied in the future, their research and development will become increasingly subdivided and specialized, and top-level design will become increasingly significant.

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