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Recent advances in fuel cells based propulsion systems for unmanned aerial vehicles

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Abstract

Unmanned aerial vehicles are an emerging technology that can provide a superior option in obtaining remote data with less time, lower cost as well as higher safety compared to piloted aerial vehicles. Although promising, the performance of propulsion systems in unmanned aerial vehicles still needs to be significantly improved to meet the requirement for executing increasingly difficult missions. Due to the higher efficiency and better reliability comparing to conventional combustion engines, electrical systems with no greenhouse gas emission and low noise and vibration attract much more attention. Among them, fuel cells, as an advanced power generation technology, are regarded as alternative power sources in electrical systems because they offer higher energy density to extend the duration of flight. For the same energy capacity, the weight of fuel cells is 3.5 times lower than that of lithium-ion batteries, resulting in much preferable specific energy. This review article provides a general description of the working principle of fuel cells and the category of unmanned aerial vehicles, introduces two types of propulsion systems that involve fuel cells, i.e., pure fuel cell system and hybrid system, describes the design methods and simulation cases, as well as summarizes the practical flight tests.

Keywords: Fuel cells; Unmanned aerial vehicles; Propulsion systems; Design and simulation; Flight tests

1. Introduction

As a variety of complicated missions inadaptable for humans are arising in both military and civil fields such as visual condition inspections [1], mechanical devices have been adopted to carry out the missions in consideration of the safety, viability, and efficiency [2]. In remote sensing and data acquiring missions, unmanned aerial vehicles (UAVs) that are expected to be the most appropriate candidate have received ever-increasing attentions and made great progress in hyperspectral imaging for agriculture and forestry [3], UAV regulations [4], wireless sensor networks [5], communication between the UAVs and the ground control station [6], and UAV system design [7] in recent decades. For civil use, applications of UAVs can be concluded as follows: (1) scientific research and remote sensing [8], (2) forestry monitoring to protect the endangered species and in case of bushfire [9], (3) rapid detection of the disaster area after earthquakes, tsunamis, and hurricanes for subsequent rescue [6, 7, 10], and (4) seasonable inspection for the survivors in hazardous situations including conflagration, gas poisoning, and house collapse so as to increase the possibility of saving lives [11]. For military use, UAVs are the first choice to execute intelligence, surveillance, and reconnaissance (ISR) missions in the battlefield due to the dangerous situations that may lead to unnecessary sacrifice [12]. For instance, the UAVs equipped with infrared camera can still work at night [13]. It has no alternative but employs UAVs to remotely collect the information inside buildings, closed channels, and narrow pipes [10]. In general, UAVs provide an admirable option to acquire remote data with less time, lower cost as well as higher safety compared to piloted aerial vehicles.

The most crucial component of a UAV is the propulsion system which supplies energy to drive itself to execute missions, because the flight endurance, specific energy, and specific power are substantially influenced by the characteristics of the propulsion system. Briefly, the specific power plays an important role in the maximum speed, load capacity, altitude of flight, and the climbing rate. The specific energy has dominant effects on the flight endurance. Initially, conventional engines were employed as the power sources. However, the conventional engines exhibit less competitive in terms of the total weight, vibration, and noise comparing to electrical systems. Additionally, the green gas emission and air pollution problem should be taken into consideration as the environmental issues have raised growing concern. For these reasons, the environmental problems are dramatically alleviated when electrical systems replace the conventional engines as the propulsion systems. Meanwhile, the electrical systems offer less weight, which contributes to higher specific energy that is beneficial for long-endurance missions. Currently, batteries that are the most common energy storage systems in the electrical systems to power UAVs are replacing the conventional combustion engines gradually, due to their superior features in efficiency, reliability, noise, and vibration. Among various batteries, lithium-ion batteries have been successfully utilized in various applications because of their higher specific power, longer cycle life, and lower self-discharge property [14, 15]. However, a critical issue associated with the use of lithium-ion batteries is the excessive weight, resulting in lower specific energy and specific power around 75-200 Wh/kg and 500-2000 W/kg, respectively [16]. The insufficient specific energy of lithium-ion batteries may diminish the flight endurance and increase the operational cost of UAVs. In addition, there are several other issues of concern. Firstly, lithium-ion batteries are vulnerable to short-circuiting and overcharging, which is harmful to the long-time operation. Secondly, the operation temperature of lithium-ion batteries will increase due to the heat generation through reactions. Once the temperature reaches the critical point, not only the batteries will be burned, but also the UAVs will be destroyed. Thirdly, the heat generated by batteries will be discovered by an infrared detector. Particularly in military missions, UAVs are expected to be utterly quiet and stealthy to guarantee obtaining the required information without being detected. Notably, the recycling processes of lithium-ion batteries are also of great environmental concern.

Among various power suppliers, fuel cells have been introduced to UAVs serving as power supply, since it is a green and efficient energy-conversion technology [17, 18, 19, 20]. It was demonstrated that fuel cells output a constant power with less weight than batteries, indicating that specific energy and specific power of the fuel cell powering system are both higher [14]. It was reported by Chen et al. [16] that hydrogen fuel cells could offer specific energy and specific power up to 800-10000 Wh/kg and 500 W/kg, respectively. In addition, the efficiency of hydrogen fuel cells is approximately 44%, which is twice higher than that of internal combustion engines. Since compressed hydrogen is selected as the fuel for fuel cells in these UAVs, the final product is only water, resulting in a zero emission. Another feature of fuel cells are low noise and low infrared signals [21]. Although promising, it is believed that the currently developed UAVs powered by fuel cells is immature in the aspects of further reduction in weight, volume, and cost. The main problem of fuel cells is the relatively low specific power, imposing restrictions on the missions that require a high specific power. A solution to this problem is to hybridize fuel cell with lithium-ion batteries, which exploits the superiority of both batteries and fuel cells, thereby creating a highly responsive hybrid system possessing a high specific power, while maintaining the significant advantage of high energy density [22]. In addition, the electricity generated by fuel cells can be partially used to power the UAVs and the remaining can be stored in batteries for further use. The UAVs running on hydrogen fuel cells with reduced weight are able to execute the missions not requiring high specific power, which are used be carried out by UAVs running on internal combustion engine. Since the issue of specific power is resolved in hybrid system, UAVs running on hybrid system are capable of performing all kinds of the missions.

This review starts with a brief introduction to working principles of two types of fuel cells, i.e., hydrogen fuel cells and direct methanol fuel cells (DMFCs). Tremendous research has been conducted on hydrogen fuel cells in UAVs, while limited research has been devoted into DMFCs in UAVs. Secondly, three UAV categories are discussed, including fixed wings, rotary wings, and flapping wings based on the way of propulsion and lift. Thirdly, detailed descriptions of hydrogen fuel cells and hybrid propulsion systems are given and three common design methods defined by parametric models and design criteria are summarized. Fourthly, we summarize the theoretical simulation results and practical flight testing results, in order to offer a comparison reference for performance evaluation. Finally, remaining challenges and future perspectives are highlighted.

2. General description

2.1. Hydrogen fuel cells

The utilization of fuel cells in powering UAVs has attracted numerous attentions due to the remarkable advantages and bright future [23]. Among various fuel cells, polymer electrolyte membrane fuel cells (PEMFCs) with hydrogen as fuel and oxygen as oxidant are the most promising candidate for powering UAVs, because they have a quick start-up and a high specific energy, and they have been extensively studied and broadly utilized in a diversity of practical cases [24, 25, 26]. The only product is water and no other harmful emission exits, which is another attractive point in terms of the environmental issues [27].

Typically, the conventional PEMFC is composed of three main components, i.e., an anode, a proton exchange membrane (PEM), and a cathode, as shown in Figure 1 [28]. It can be seen from the Figure 1 that anode and cathode are placed in contact on opposite sides of the PEM. Each electrode is composed of a diffusion layer (DL) and a catalyst layer (CL). The DL is always made of porous materials and functioned as the CL support and fuel micro-channels. The fuel is continuously supplied from the flow channel on the bipolar plate and is distributed evenly to the CL. The CLs are usually made of electrocatalysts mixed with ionomer, resulting in the formation of triple-phase boundaries (TPBs) for electrochemical reactions, i.e., hydrogen oxidation reaction (HOR) and oxygen reduction reaction (ORR).

On the anode, hydrogen is fed to the anode flow channel and transported through the anode DL, finally to the anode CL, where hydrogen is reduced to protons and electrons. The anodic reaction is:

$$H_2 \rightarrow 2H^+ + 2e^- \qquad E_a^0 = 0V \qquad (1)$$

Then, the generated protons are conducted through the PEM to the cathode. On the cathode, oxygen supplied by the cathode flow channel is transported through the cathode DL to the cathode CL, where oxygen reacts with protons to produce water:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad E_c^0 = 1.23V \qquad (2)$$

Therefore, the overall reaction combining the HOR given by equation (1) and the ORR given by equation (2) is expressed as follows:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad E^0 = 1.23V \qquad (3)$$

It should be noted that the theoretical cell voltage cannot be realized due to a series of irreversible losses caused by activation, Ohmic, and mass-transport processes [29].

2.2. Methanol fuel cells

Hydrogen is usually obtained from natural gas and water splitting, leading to a high production cost. Meanwhile, compression and liquefaction, the hydrogen storage methods, also require extra cost [21]. For the compression process, the storing pressure increases from 200 bar to 700 bar in order to enhance the hydrogen quantity. Under such high pressure, the adoption of more resistant tanks is necessary, whose weight is supposed to be high. For the liquefaction process, a cryogenic system is required to control the hydrogen at a temperature of 20.4 K, thus hydrogen is in liquid state. Hence, liquid-fuel feeding DMFCs have been adopted to UAVs, offering higher specific energy and potentially better endurance. Moreover, methanol is much easier to be transported, stored and handled due to its liquid phase, which results in the avoidance of complicated and expensive auxiliary facilities and reduces the cost consequently. In addition, methanol is more abundant than hydrogen due to the resources from biomass, which further lowers the cost [30]. However, there are two issues hindering the introduction of DMFCs into UAVs. One is the lower energy efficiency comparing to hydrogen fuel cells, which is derived from the sluggish kinetics of methanol oxidation reaction (MOR), and the other is the catalyst-poisoning problem by CO species during MOR, resulting in the performance degradation for long-time operation [31, 32].

The construction of DMFCs can be just borrowed from PEMFCs, consisting of an anode DL, an anode CL, a PEM, a cathode CL, and a cathode DL. On the anode, liquid methanol is fed to the DL and diffuses to the CL, where methanol is oxidized to produce carbon dioxide, protons, and electrons in the presence of water:

$$CH_3OH+H_2O \rightarrow CO_2+6H^++6e^- \qquad E_a^0=0.02V \tag{4}$$

Afterward, the generated protons are transported through PEM to the cathode, where they participate in the ORR process:

$$\frac{3}{2}O_2+6H^++6e^- \rightarrow 3H_2O \qquad E_c^0=1.23V \tag{5}$$

Combining equation (4) on the anode and equation (5) on the cathode, the whole reaction can be expressed as follows:

$$CH_3OH+\frac{3}{2}O_2 \rightarrow CO_2+2H_2O \qquad E^0=1.21V \tag{6}$$

It can be seen that the theoretical voltage of DMFC is a little inferior than that of hydrogen fuel cells. Similarly, the actual voltage of a DMFC is much lower than the theoretical one, due to activation, Ohmic, and concentration losses. In addition, the practical operating voltage of DMFC is much lower than that of hydrogen fuel cells, which is attributed to the methanol crossover phenomenon. The methanol transported from anode to cathode will react with oxygen on the cathode, resulting in the mixed potential and low voltage.

2.3. Classification of UAVs

UAVs can be divided into various types based on different principles. In this paper, we classify UAVs into three categories based on the way of propulsion and lift generation, i.e. fixed-wing UAVs, rotary-wing UAVs, and flapping-wing UAVs. For designing all the UAVs, the weight budget and the power budget should be taken into consideration seriously. As a result of the extra power consumption caused by the auxiliary facilities, it is necessary to keep the total weight of the vehicle as low as possible [13].

2.3.1. Fixed-wing UAVs

UAVs with fixed wings are the most developed among three above-mentioned categories, as they are the most well-established [33]. Since this type of UAV is not able to hover and a relatively high speed of 6 to 20 m/s is required for flight, outdoor missions including remote sensing, forestry monitoring in case of bushfire and rapid detection of the disaster area are perfectly appropriate. However, this type of UAV is improper to indoor activities, because they are incapable to hover or fly at low speed [13]. For the fixed-wing UAVs, the minimum power to ensure a level flight can be expressed [13]:

$$P=\frac{TV}{\eta_p}=\frac{W}{L/D}\frac{(2W/S\rho C_L)^{1/2}}{\eta_p} \tag{7}$$

where T is the thrust, V is the forward velocity, η_p is the propeller efficiency, W is the total weight of the UAV, S is the wing surface area, ρ is air density, and C_L is the lift coefficient. It is should be noted that L/D defined as lift-to-drag ratio refers to aerodynamics efficiency.

2.3.2 Rotary-wing UAVs

The second category is the rotary-wing UAV, which is similar to the helicopter, indicating that this type of UAV is capable to hover and execute vertical take-off and landing (VTOL). Therefore, the rotary-wing UAVs are able to undertake the indoor missions that are challenging for fixed-wing counterparts. In view of the position and number of the propellers, seven common configurations for rotary-wing UAVs are shown in Figure 2, including (a) conventional, (b) ducted coaxial, (c) conventional coaxial, (d) rotors side by side, (e) synchropter, (f) conventional tandem, and (g) quad rotor (or multi-rotor, including hexa-rotor, octa-rotor and more rotors) configurations [13]. The conventional configuration and ducted coaxial UAVs are both excellent in maturity of technology, hover efficiency, ease of payload packaging, and reliability, but poor in compactness of folding and vibration. Moreover, the ducted coaxial UAVs are inferior in aerodynamic cleanliness. The conventional coaxial UAVs are similar to the conventional configuration, in spite of its superiority in compactness of folding. In addition, the UAVs with rotors side by side and the conventional tandem UAVs are similar in their configurations, despite the difference in aerodynamic interaction between two rotors. Comparing to the conventional configuration, these two configurations exhibit outstanding aerodynamic performance. The quad rotor UAVs are quite different, showing credible controllability, compactness of folding, and simplicity of control system than other types. However, aerodynamic cleanliness and maturity of technology of this configuration are not satisfying, due to the fact that four motors are required. These four motors render the UAVs typically heavy and difficult to be miniaturized [33]. Generally, when designing a rotary-wing UAV, it is essential to take it into consideration that each specific mission requires special demands and these demands may not be met simultaneously. Therefore, it is critical to combine these different features and choose a best configuration [34]. Typically, for UAVs that can hover, the minimum power requirement can be expressed by equation (8) [13]:

$$P=\frac{TV_h}{M}=\frac{W}{M}\left(\frac{W}{2S\rho}\right)^{1/2} \tag{8}$$

where M is the figure of merit of the rotor and V_h is the induced velocity in hover. Currently, the crucial drawback of rotary-wing UAVs is the endurance, because their hovering and VTOL motions consume a large amount of power and their aerodynamic efficiency is low compared to the fixed-wing UAVs [35].

2.3.3 Flapping-wing UAVs

The last category is the flapping-wing UAV inspired by birds and insects. It is believed that integrating lift and thrust together with stability and control mechanism is possible in this type of UAV [36]. However, the distinction between ornithopters (bird-like ones) and entomopters (insect-like ones) is the variations in angle of incidence. The ornithopters generate lift by flapping wings up and down with small synchronized variations of angle of incidence, while entomopters generate lift by flapping wings up and down with large and rapid change of angle of incidence [37]. Hence, entomopters receive much more attention than ornithopters, due to the generation of more lift leading to the ability of VTOL and hovering. The insect wing beats are generated by contraction of muscles. In order to modify the wing beats, several methods are proposed, including linear actuators [38], electroactive polymers (EAP) [39, 40], and rotary actuators such as electric motors [41, 42]. On the other hand, the shape of the wings also plays an important role in flapping-wing UAVs. It was reported by Tanaka et al. [43] that the rough wings exhibited better performance than the smooth wings due to large up-down motion of the body and large cyclic changes in the body angle of attack, increasing the upward aerodynamic force during downstroke.

In summary, three types of UAVs have their respective limitations. None of them can meet all the missions. The advantage of fixed-wing UAVs is the less thrust-to-weight ratio due to the additional lift provided by the wings [13], but they are not able to undertake indoor missions. The advantage of rotary-wing UAVs is that they can hover and execute VTOL to carry out indoor missions, but the solutions for power consumption and size miniaturization are extremely urgent [44]. Flapping-wing UAVs are similar to the rotary-wing UAVs, but the system is more complicated. Therefore, they are even more difficult to be miniaturized. Hence, the optimal design of UAVs depends on the specific missions.

3. Power system designs

No matter what specific mission that the UAVs are applied to, the cost, power, and flight endurance are three main constrains. Since reducing cost is the critical research focus for widespread applications, the current attentions are paid to improving the power and flight endurance, both of which are related to the power sources. Hence, the power system designs are extremely crucial, which are expected to possess advanced specific power and specific energy, as well as high efficiency. In general, the specific power determines the maximum speed, load capacity, altitude of flight, as well as the climbing rate. The specific energy has decisive effects on the flight endurance. A higher specific energy can avoid the frequent process of refueling and recharging [45, 46, 47].

Among various power sources, the specific power and specific energy of UAVs powered by internal combustion engines are remarkable, which is usually one-magnitude-order higher than that of electrical motors [48, 49, 50]. However, as the present dominant utilization of UAVs is in military field, the noise caused by the internal combustion engines operation is more likely to be detected and thus leads to the failure of missions [51, 52]. In addition, the propulsion efficiency of internal combustion engines is generally around 40% and at most 48%, while the propulsion efficiency of electric motor is always exceeding 90% and reaching close to 100%. Therefore, tremendous efforts have been made into the UAVs powered by fuel cells and lithium-ion batteries due to its low acoustic and heat emissions [53]. In addition, as fuel cells have made great progress recently, the weight of the whole fuel cell system decreases significantly, yielding a high specific power and specific energy. The following two sections will introduce two types of power systems: pure fuel cells and hybrid systems.

3.1. Pure fuel cells

Particularly, since hydrogen fuel cells have many successful practical applications, numerous researches have been conducted on hydrogen fuel cells, which is the most mature fuel cell technology for powering UAVs [54]. Bradley et al. [55] established a 500-W PEMFC powerplant that was incorporated into an aircraft subsequntly with variable cathode flow-rate control, liquid cooling, self-humidification, and variable period anode purging. Figure 3 illustrated the aircraft, the fuel cell stack as well as the system specifications. It was indicated that three conditions, including idle, high-power, and nominal cruise, were involved in the fuel cell operations. The Sankey diagrams in Figure 4 depict the performance and efficiency of the powerplant.

Under the idle condition, a low heating value (LHV) of 227 W supplied by 1.26 Standard L min^{-1} of hydrogen was obtained, while a waste of 168 W derived from the anode purge was detected. A gross electrical power of 26 W was generated by the fuel cell. Although deficient, it was enough to balance the plant and aircraft controls. When the UAV began to accelerate and climb, the fuel cell was under full load operation and produced its maximum power. It was seen from the Figure 4 (b) that a LHV of the consumed hydrogen flow is 1056 W out of the LHV of the input hydrogen flow of 1197 W, suggesting that the hydrogen utilization reach 88%. In addition, the net electrical power, rotational power, and propulsive power were 323, 238, and 168 W, respectively, indicating that the efficiency of controller was 74% and the efficiency of the propeller was 71%. The reason for the inferior efficiency of propeller was the low speed and advance ratio, resulting in the efficiency of power system as low as 14%. It was worth noting that advance ratio, a useful non-dimensional velocity in helicopter and propeller theory, is defined as the ratio of free-stream fluid speed to the propeller tip speed:

$$J=\frac{V_a}{nD} \tag{9}$$

Where V_a is the free-stream fluid velocity, n is the rotational speed of propeller in rotations per second, and D is the diameter of the propeller.

Under the nominal cruise condition, the aircraft was operating at a steady altitude of approximately 10 m and a constant airspeed of 13.6 m s^{-1}. The efficiency of motor controller, the propeller, and the power system were 66%, 80%, and 18%, respectively. Comparing to the high-power condition, the efficiency of motor controller was a little lower due to the lower duty cycle. However, the efficiency of the propeller was higher due to the higher advance ratio. As a result, the efficiency of the total power system was higher than that of the high-power condition.

To further reduce the weight and volumn of power system, Furrutter et al. [56] designed a fixed-wing UAV powered by a power plant in the form of a 100-W hydrogen fuel cell, which was much smaller than the 500-W PEMFC, indicating that it was feasible to maintain an aircraft in level flight via a small fuel cell with 100 W output. They also proposed that the PEM could be disassembled from the fuel cell stack and placed in series under the wing, leading to the absence of removing the casing of stack and thus the reduced weight. Swider-Lyons et al. [57] demonstrated that changing gaseous hydrogen to liquid hydrogen was an alternative method to enhance the endurance of the flight. Since liquid hydrogen possessed 3-time higher energy density (Wh/L) compared to gaseous hydrogen stored at 5000 psi, less volume was required if the gaseous hydrogen was replaced by the liquid hydrogen. Another advantage of the liquid hydrogen is that it can be stored at near 50 psi, which is much lower than 5000 to 10000 psi for the compressed hydrogen. As a result, the lower storage pressure was benefical to exclude the demand for a massive carbon-overwrapped pressure vessel, as well as to permit lighter weight storage vessels, improving the specific energy of the power system.

Despite adding hydrogen in advance, fabricating an on-site hydrogen generator into the UAV is an alternative choice, which abandons the use of a hydrogen storage system that occupies a large proportion of the weight of the power system. Currently, chemical hydrides have been regarded as an appropriate hydrogen source. Among them, the utilization of $NaBH_4$ alkaline solution as hydrogen source has been studied [19, 58, 59, 60], due to the following advantages: (1) it is stable and nonflammable; (2) it is non-toxic; and (3) it possesses high hydrogen capacity (10.8 wt.%). Kim et al. [58] developed a fuel cell system consisting a hydrogen generator as shown in Figure 5 (a). The blue dashed box shows how the hydrogen generator functions, consisiting of a fuel cartridge, a micropump, a reactor, a gas-liquid separator, and a dehumidifier. With the assisstance of a micropump, the $NaBH_4$ solution stored in the fuel cartridge was pumped into a reactor, where the hydrolysis reaction of $NaBH_4$ took place to produce gaseous hydrogen according to

$$\mathrm{NaBH_4+2H_2O \rightarrow NaBO_2+4H_2} \tag{10}$$

Cobalt was selected as the catalyst because of its high activity towards $NaBH_4$ hydrolysis [61] and low cost. Finally, the silica acted as a trapper to absorb water and pure gaseous hydrogen was obtained. Nevertheless, hydrogen generation rate was unstable due to the clogging phenomenon in the hydrogen flow channel by the crushed support particles. Hence, it was necessary to place a mesh filter to prevent the clogging phenomenon. It was indicated that a stable and sufficient hydrogen generation rate of 1.0 L min^{-1} was achieved. It was reported by Okumus et al. [19] that a higher hydrogen generation of 5 L min^{-1} was achieved with 20 wt. % $NaBH_4$ and 3 wt. % NaOH alkaline solution in a cobalt-based catalyst reactor. However, one remaining constrain could be seen from Figure 5 (b) [59] that the two fuel tanks occupied the major portion of the total volume, and it was difficult to reduce the volume and weight of the entire fuel cell system due to the huge hydrogen generator components. Recently, Kim et al. [60] proposed a volume-exchange fuel tank to intergrate the $NaBH_4$ solution tank and the $NaBO_2$ solution tank, leading to the minimization of the volume of the fuel cell system as shown in Figure 5 (c). Figure 5 (d) illustrates the working principle of the volume-exchange fuel tank. Initially, the tank was full of $NaBH_4$ solution and the rubber bag was empty. With the operation of the pump, a vacant volume was formed in the fuel tank, which was filled by $NaBO_2$ and hydrogen in the rubber bag subsequently, indicating the completion of the volume-exchange. Moreover, there is no problem with fuel sloshing during the flight. It was demonstrated that an average hydrogen generation of 1.33 L min^{-1} was maintained for 30 min, and $NaBH_4$ supply was interrupted for 5 min to save the fuel because the power was not required all the time. The pump was restarted and the hydrogen was generated immediately. Although the generation rate was decreased to 1.21 L min^{-1}, it was still sufficient to feed the fuel cell.

In summary, the remarkable advantage of hydrogen fuel cells for powering UAVs is the approximately 80% reduction of the weight, which improves the specific energy and power simultaneously. In addition, the emission of heat and noise from the fuel cell system is low, avoiding being detected by monitoring equipment during the mission. However, the sources and storage of hydrogen need to be further investigated. Another critical issue is associated with the noble metal catalysts that significantly increase the cost. In spite of the remaining challenges, the bright future of the UAVs powered by hydrogen fuel cells can be foreseen.

3.2. Hybrid systems

A hybrid electric vehicle (HEV) is a vehicle in which propulsion energy is available from two or more types of energy stores, sources, or converters [62]. Comparing with single propulsion system, a hybrid one exhibits better characteristics as follows: (1) the size of the hybrid system can be reduced because both components are allowed to be downsized with respect to the required average power [63]; (2) the energy demand in the transient state allows fast variations, which would be limited by the delivery system of a single fuel cell [64]; (3) it is still possible to operate the hybrid power system when components are malfunctioning [65]; and (4) the hybrid system possesses the capacity to deal with intermittent availability of renewable energy sources [66]. Nishizawa et al. [67] proposed a hybrid system consisting of fuel cell stacks, Li-ion battery packs, and two diodes. Comparing to the conventional hybrid system, the difference lied on the replacement of the DC/DC converters by two diodes, changing an active hybrid system that utilizes DC/DC converters to actively control the power sharing between the fuel cell and the storage device to a passive hybrid system, which is directly connected the fuel cell and storage device to the DC bus without the use of power converters [67]. It should be noted that the passive hybrid configuration possesses several superiorities, including low power loss, low cost, and simple architecture. It can be seen from Figure 6 (a) that the initial power output was derived from the fuel cell and the cell voltage was rapidly decreased. Once the cell voltage reached the same value as that of battery, the fuel cell and battery were discharged simultaneously at the same voltage. Afterwards, the discharging current of the battery exceeded that of the fuel cell, which was attributed to the current of fuel cell being saturated due to the lack of cooling. Finally, the cell voltage was increased significantly and the battery stopped discharging. It was shown from Figures 6(b) and 6(c) that the quick response of the battery output completely compensated for the delay in fuel cell output response, indicating that the direct hybrid system was applicable to high-frequency electric loads. The power variations are shown in Figure 6(d). Obviously, the load power was not in accordance with the gross power that was the summation of fuel cell and battery powers, resulting from the power losses at the diodes, copper cables, connectors, and relays. The power loss was not remarkable when the gross power increased, indicating that the hybrid power system is highly efficient. Verstraete et al. [22] evaluated the performance of Horizon Energy Systems’ AeroStack hybrid, fuel-cell-based powertrain that was an active hybrid system on a UAV. Compared to the passive hybrid system, the active one possesses two advantages: one is increasing the peak output power while reducing the weight and volume [68], and the other is increasing flexibility for the design [69]. It was indicated that the fuel utilization of the AeroStack exceeded 90% from 50 W to 200 W, and in this power range, the electrical efficiency was above 50%. In addition, the fuel-cell controller prevented the system from operating in the region of high concentration losses. In addition, the dynamic polarization curves showed an obvious hysteresis effect, which was attributed to the slow equilibration of water content. Therefore, the membrane did not possess the sufficient humidity for efficient proton conductivity. The other important power source, the AeroStack system's LiPo battery, was proved to play a critical role in the dynamic response of the system, which can adapt the system to rapid load changes and protect the fuel cell from membrane dehydration and fuel starvation.

Subsequently, the role of the battery in the hybrid system was extensively investigated by Verstraete et al. [70]. It was demonstrated that the coulometric capacity and current rating of the battery significantly affected the performance of the hybrid system. In response to sharp and large power changes that often occurred during mission execution, the battery with a small capacity, but high current rating behaved similarly to the battery of a higher capacity, but smaller current rating. The power-management board charged the 1350 mAh battery to 24.2 V, which was almost 70% of the full capacity initially at 0.85-0.90 A, and subsequently at a constant voltage. Charging the battery required the consumption of approximately 15 standard liters fuel, which implying that the endurance was decreased equivalently. It was emphasized that the balance among battery boost capability, boost-power availability, battery mass, and mission endurance should be taken into consideration for specific missions when choosing the battery.

Despite the typical hybrid power systems consisting of two power sources, a hybrid power system comprised of three power sources, including solar cells, fuel cell stack, and batteries, have been proposed [71, 72]. Recently, Gadalla et al. [71] developed a small UAV using photovoltaic panels to cover the wing area, a lithium-polymer battery as well as a PEMFC to constitute the hybrid power system. It was demonstrated that the endurance of the UAV with this hybrid system was 53,396 s, which was almost as twice as a UAV powered by a single fuel cell (28,173 s). As a result, the enhanced endurance could lead to longer operation and fewer takeoffs and landings. Therefore, the operation cost was lowered and the risk of damage was reduced. In addition, an increased current requirement from 4.6 A to 8.6 A caused by increased drag resulted in a decreased endurance from 50,000 s to 40,000 s. Typically, the variation of solar flux due to the change in time of the day or weather conditions significantly affected the PV power output, further to the flight endurance. It was reported that the promotion of PV power output from 65 W to 116 W gave rise to increasing endurance from 39,000 s to 47,000 s. Figure 7 shows the layout of the UAV, denoted as the Electric Aerial Vehicle-2 (EAV-2), which was designed as a low-speed, long-endurance UAV to conduct ground observation and ISR missions using its loaded camera by Lee et al. [72]. The three power sources sharing the same voltage range were directly connected to the bus without a power converter. The test results showed that the average power consumption and the maximum take-off power reached 145 W and 1.0 kW, respectively. As EAV-2 took off at night, the fuel cell was the only power source to match the average power consumption. Meanwhile, the battery pack was charged to 88% of its full capacity with a high voltage of 28.9 V at the moment of take-off. As EAV-2 reached the target altitude, the system voltage was stabilized at around 26.5 V. In the daytime, the solar cells came into operation and became the primary power source. Since the power produced by solar cells exceeded the power requirement, the batteries could be charged by the extra power, resulting in an enhancement in system voltage. The batteries attenuated the power fluctuations and momentary changes in power. It was indicated that each power source acted as it was designed anteriorly to export the propulsion power for the successful flight, in case of excessive voltage, excessive current, failure of the fuel cell, and solar power shortage due to climate change.

In summary, the power system is believed to be the most critical module in a UAV, as it affects two key parameters that are specific energy and specific power remarkably. Introducing fuel cells into the power system design is attractive due to its unique advantages: (1) negligible noise and vibration as well as low emissions; (2) more efficient than fossil fuel based technologies due to the absence of combustion; (3) higher specific energy and specific power than batteries due to the reduced weight; and (4) flexibility and reliability of operation. Although promising, it is well known that coupling a fuel cell system with electric energy storage devices can lead to better performance than operating with a fuel cell system alone [73]. It can not only store the extra energy supplied by fuel cells into batteries for later use, but also elevate the specific power. Meanwhile, the advantages of each power source can be exploited, resulting in the combination of high-energy-density fuel cells and high-power-density secondary power source. Hence, a longer endurance and a higher efficiency will be guaranteed.

4. **Theoretical designs and simulations**

Since UAV systems are becoming more complex, together with the cost of making physical prototypes getting more expensive, mathematical design and simulation can play a significant role in the design of virtual UAV prototypes and serve as an economical and useful tool. However, creating a design environment that is flexible and modular in coupling of operational and systems capabilities is challenging [74]. Generally, in the design environment, the systems capabilities are related to a set of disciplines including aerodynamics, power, propulsion, structure, and control. A given UAV can be verified by the disciplines whether the system model can fulfill the desired requirements. During the conceptual design, many alternative systems may be taken into consideration. Hence, only if the design environment is flexible and modular enough, the various systems models would be integrated and scripts connecting the different systems would be allowed. In addition, variable fidelity of the design environment is one of the key characteristics as well. Low fidelity tools are valid for rapid evaluation of the design space, while high fidelity tools are employed to refine the performance predictions of a specific design and converge toward a final system architecture [74]. It is worthwhile to mention that three different design methods have been proposed and utilized, which are classified by the scope of their parametric models of the aircraft systems and their definition of design criteria [75]. The first design method is scaling of a predesigned fuel cell, which is combined with parametric aircraft model and design environment subsequently. This method is convenient due to the absence of detailed fuel cell subsystem models, but the limited information about the fuel cell system hinders subsequent designs and implementation tasks. The second design method is opposite to the first method, which means that the fuel cell and its subsystems are designed in advance, regardless of detailed consideration of the aircraft. Similarly, this method divides the UAV design into two independent designs, suggesting that the second method is analogously convenient. However, the interactions between the powerplant and the aircraft are ignored. The third one is to consider the design of the fuel cell and the aircraft simultaneously. Obviously, the integrated design process is beneficial for modeling the interactions between the powerplant and the aircraft in detail. However, the design space is enlarged, resulting in the higher design complexity and greater computational costs. It is suggested that a tradeoff between information and cost should be made in terms of the practical situation. Gur et al. [76] proposed a design approach, so-called multidisciplinary design optimization (MDO), which took all different design goals and constraints into consideration simultaneously. Two critical performance indicators that were loiter time and the rate of climb were selected as an example. Notably, loiter time was directly associated with main reconnaissance task, and the rate of climb was straight related to the survivability and safety of the vehicle. The constrain between loiter time and rate of climb lay on the fact that as the rate of climb demand was increased, the loiter time was decreased due to the enhancement of engine mass. Consequently, when designing the propulsion system, it was essential to evaluate all the components concurrently, including propeller, motor, and power source.

Based on cruise simulation, Renouard-Vallet et al. [77] indicated that hydrogen fuel cells exhibited to be the most potential candidate for long endurance. Lee et al. [78] simulated the behavior of UAV powerplant consisting of fuel cells, solar cells, and a battery both in active and passive management, which was beneficial for determining the capacities of the power sources and confirming their characteristics in the system. It was shown that the power system operated reasonably in the passive management without active control. The primary power sources were supplied by the solar cells and fuel cells. When a higher power was required during take-off and transient flight, the battery set out to provide the extra power supply. In addition, the solar cells produced 46.9% more power at the summer solstice than at the winter solstice, resulting in a favorable situation that the power sources were solar cells and fuel cells. Meanwhile, the battery was charged during the flight. In an active management, the power system was controlled individually, which maintained a minimum level of state of charge (SOC), leading to efficient power distribution and great system safety. Recently, the endurance of four types of power supply, including fuel cell, lithium iron phosphate battery ($LiFePO_4$), lithium polymer battery, and nickel based cathode battery ($LiFP_6$), was investigated by Donateo et al. [79] via simulations. Particularly, two endurances were studied. One was gross endurance related to the endurance at level flight, and the other was net endurance associated with mission-based endurance. As seen in Figure 8 (a) that when the initial content of energy on-board was all kept at 2 MJ, the fuel cell exhibited the worst endurance. When the energy content was continuously increased, the gross endurance of UAVs powered by fuel cell was promoted dramatically from 4.8

h to 14 h, while the endurances of other three power sources were gradually decreased. It was because the change of aircraft empty mass, powertrain volume and wing area to match the increment of content energy was negligible for a fuel-cell based aircraft; on the other hand, the battery-based aircraft was required to be redesigned and the corresponding aircraft empty mass, powertrain volume and wing area increased significantly, yielding the reduction of endurances. An interesting phenomenon was found in a simulation of long-term test by Renau et al. [18] that in a PEMFC/Li battery hybrid system, the water vapor accumulation reduced the supply amount of hydrogen and oxygen in the stacks and caused voltage fluctuation. Hence, gas purge procedure was believed to be important in achieving optimal performance.

In summary, the nature of these studies is the design procedure for modeling the characteristics of the UAV powerplants and airframes. The fundamental purposes of design and simulation can be concluded as follows: (1) characterize the design tradeoffs and optimize configurations of aviation-specific fuel cell powerplants, (2) compare the performance of fuel cell aircraft to conventional aircraft, and (3) function as a preliminary design tool for a fuel cell based UAV.

5. Practical flight tests

After completing the design, it is critical to apply the prototype UAV into practical flight tests. Currently, flight tests are focused on achieving level flight for verifying the aircraft's general handling and stability characteristics. Generally, two tests are required: one is to determine the aircrafts characteristics and then set the controller for optimal power and control scheme efficiencies, and the other is to operate under optimal conditions and record the data. Afterwards, the experimental results can be used to tune the autopilot controls and power consumption characteristics. The performances reported in recent literatures have been concluded in Table 1 [17, 55, 60, 71, 72, 79, 80, 81, 82, 83, 84, 85, 86, 87].

5.1. Fixed-wing UAVs

An initial flight tests of a hydrogen fuel cell powered UAV were conducted by Ward et al. [88]. It was indicated that the UAV was lifted to a maximum altitude of 2 m and landed safely in the first flight about 75 m from the origin point. The throttle setting was reduced and airborne time was only 17 s due to the presence of gusting headwinds. While the throttle was kept at a relatively constant setting in the second flight, the altitude reached 10 m and airborne time was improved to 30 s. Afterwards, the UAV hit to the ground influenced by a strong gusting crosswind. The altitude of 10 m was too low for UAV to recover the stall wing. The starting power in the first flight was 500 W, and decreased with the diminishing throttle setting. It was showed that the power supplied by fuel cell ranged from 445 W to 500W in the second flight, suggesting the design of the UAV was feasible. A short circuit flight test was presented by Bradley et al. [89]. The aircraft accelerated with the power output of the fuel cell, starting at the 46 s. At around 70 s, the aircraft began to take off and gain altitude. The aircraft traded airspeed for altitude between 70 s and 110 s, and reached the maximum altitude of 32m at 110 s. Subsequently, the descent to landing began at 120 s. The power from the fuel cell then dropped as the aircraft deployed flaps and slowed down for landing. The aircraft landed at approximately 150 s, and decelerated to a halt. The power and speed transients after 170 s were due to ground maneuvering and taxiing. The behavior of the powerplant was also monitored during a straight-line flight test of 80 seconds duration and 1200 m distance. Based on the primary modes of use of the fuel cell powerplant, three conditions were defined: point 1 refers to the idle condition; point 2 corresponds to a high-power condition that occurs during climbing and acceleration; and point 3 is the nominal cruise condition. At the time of 3.7 s, the UAV began to ramp up the current command and the propeller speed increased from the idle condition. The full-power propulsion system current and voltage were reached at 5.2 s. The air supply compressors were then controlled to supply their maximum airflow during the takeoff and climb portions of the flight test. As the aircraft speed was increased, the propeller speed was naturally decreased even though operated at constant input power. At the time of 48 s, the aircraft ended its high power climb and began to cruise. The aircraft cruised for 8-10 seconds and started to descend and land after 57 s. Renau et al. [18] tested a passive hybrid power system consisting of a high-temperature PEMFC and a set of lithium-polymer batteries to power a lightweight UAV at a high altitude. The flight test results showed that the power exported to DC bus for the hybrid system was 1000 W with a stack efficiency of 44.3%, while that of simple powerplant was 800 W with a stack efficiency of 36.4%, suggesting that the efficiency of the stacks was improved by 7%. This improvement was ascribed to the limitation of the voltage at the main DC bus by the batteries. Troncoso et al. [90] tested a fuel cell powered UAV that consisted of a concentrated photovoltaic (CPV) array, an alkaline electrolyzer, a low pressure hydrogen buffer tank and the required power electronics. It was indicated that no obvious operational issues were found in this system, suggesting that the operation of the CPV array and the CPV inverter connected to the electrolyzer were both satisfactory. However, the overall energy efficiency of the CPV-inverter-electrolyzer system was below 40%, which was ascribed to excessively long start-up periods for the electrolyzer to generate hydrogen, the slow dynamic response due to regular pressurization and depressurization cycles of the electrolyzer, and the excessive power consumption of the electrolyzer auxiliaries. It was expected that if some optimization was conducted, mainly related to the control system of the electrolyzer, the overall energy efficiency should increase and the dynamic response of the electrolyzer could be improved. Recently, Lapena-Rey et al. [17] developed a UAV with a PEMFC powerplant and a chemical hydride hydrogen generator, in which 900 Wh was produced from 1 L chemical solution. It was demonstrated that the flight endurance of almost 4 h was achieved when it was combined with lithium polymer batteries.

5.2. Rotary-wing UAVs

Rotary-wing UAVs, which are regarded as vertical take-off and landing UAVs, are less susceptible to turbulence comparing to fixed-wing UAVs with similar sizes. They are small in size, easy to control, and used for missions that require hovering flight and high maneuverability [91]. However, negligible attention has been paid into the fuel cell powered rotary-wing UAVs, because the previous studies were focusing on the application of fuel cells into a monoplane. There was a UAV project commenced in 2016 in Foshan, China, whose objective was to manufacture and market rotary-wing UAVs propelled by a hybrid hydrogen fuel cell battery drive by 2018 [92]. The design was a quadcopter with a 700W PEMFC system fuelled from a lightweight type 3 composite tank containing hydrogen at 30 MPa pressure. The preliminary tests showed that the UAV was fly for more than an hour on hydrogen, extending the battery range by a factor 4. Recently, Belmonte et al. [93] investigated the feasibility of the application of a PEMFC to increase the flying range for a rotary-wing UAV. On one hand, the cost analysis demonstrated that the total costs of the fuel cell based UAV and battery based UAV were € 27410 and € 11320, respectively. After the costs were normalized by the lifetime, a relative reduction of costs was obtained in fuel cell based UAVs, which was attributed to the longer lifetime of fuel cells than that of batteries. On the other hand, both of the global warming potential (GWP) and cumulative energy demand (CED) of fuel cells based UAVs, which were two representative impact assessments in environmental impact, were higher than that of battery based UAVs. Similarly, after being normalized by the lifetime, the impact of production of the fuel cell based UAV and battery based UAV were 0.0109 kgCO_2/h and 0.0139 kgCO_2/h for GWP as well as 0.146 MJ/h and 0.226 MJ/h for CED, respectively. It was concluded that the choice of a final user between fuel cell and battery will be mainly driven by a combination of flying time requirements and costs.

In summary, flight tests are an integral part of the UAV to observe the fuel cell powerplant under actual operating conditions. Moreover, it provides a functional test for all the aircraft systems, and allows for final validation of the models and assumptions used during the design stage.

6. Remaining challenges and future perspectives

Since the recent decades, unmanned aerial vehicles have been increasingly gaining interest for both military and civil applications, due to their numerous advantages, such as, their capabilities to operate in adverse conditions for a human pilot, operational performances, design flexibility, low cost, and less infrastructure requirements. Although attractive, scaling down versions of larger aircrafts to unmanned aerial vehicles remains challenges. It is easily misunderstood that large aircrafts are much more complex than unmanned aerial vehicles. However, if the unmanned aerial vehicles are required to operate tasks with similar level of large aircrafts, both physical and technological challenges occur and slow down further miniaturization [94]. The activation of fuel cells is quite crucial, because fast startup is a basic requirement for the unmanned aerial vehicles. Moreover, the effect of different atmospheric variables on fuel cell performance should be extensively investigated, guaranteeing the stable power output for the unmanned aerial vehicles. In addition, the effects of the hydrogen consumption on the power distribution and fulfillment should be minimized. Another issue that has not attracted enough attention is the shift of center of gravity during the consumption of fuels [17]. As the shift may result in negative effect on the aircraft stability if the center of gravity is shifted out of the its acceptable limits. Therefore, the placement of the fuel tank is also important. For the hybrid propulsion system, the challenging task is to balance two different characteristics of electric power sources to meet load variations during the flight.

In the race of widespread applications of fuel cell powered unmanned aerial vehicles, several critical issues need to be addressed in the future: (1) weight reduction and reliability improvement of fuel cell components is necessary to meet aircraft requirements; (2) improvement of catalyst durability and reactor design are imperative to optimize hydrogen generation rate and to prevent borate clogging; (3) replacement of noble metal catalysts by non-precious metal catalysts is an effective way to reduce the cost; (4) promotion of specific power of the fuel cell stacks is desirable by means of a new design or new materials for bipolar plates; (5) fast startup of the fuel cell system and convenience of fuel recharge are especially vital in some special missions; (6) enhancement of the unmanned aerial vehicle structural stability under harsh operating environments is crucial, such as midsummer, midwinter, and rainy days; and (7) special attention should be paid to the effects of high altitude on the mission operation due to the oxygen supply being hindered.

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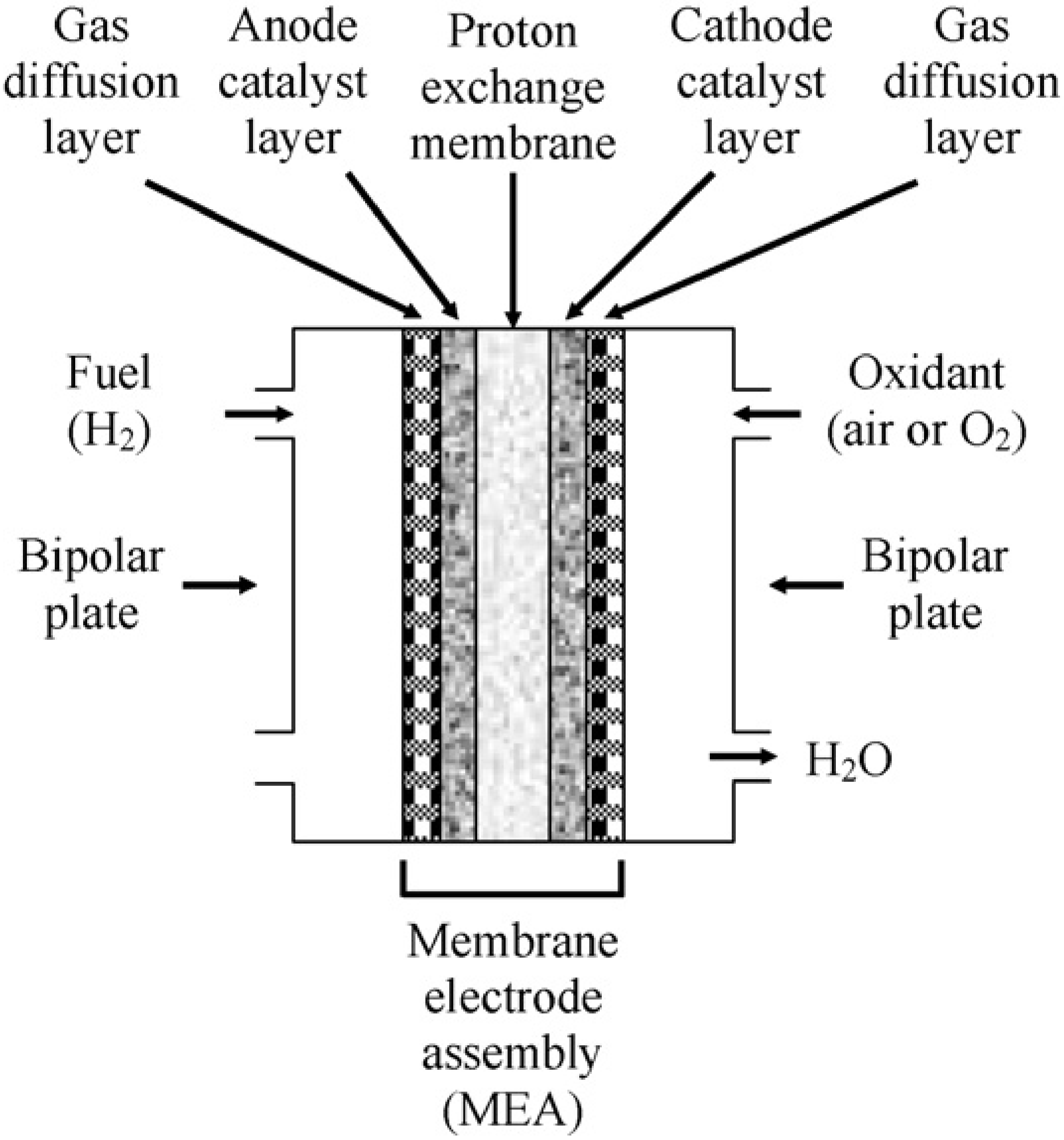

Figure 1. Schematic of a typical proton exchange membrane fuel cell [28].

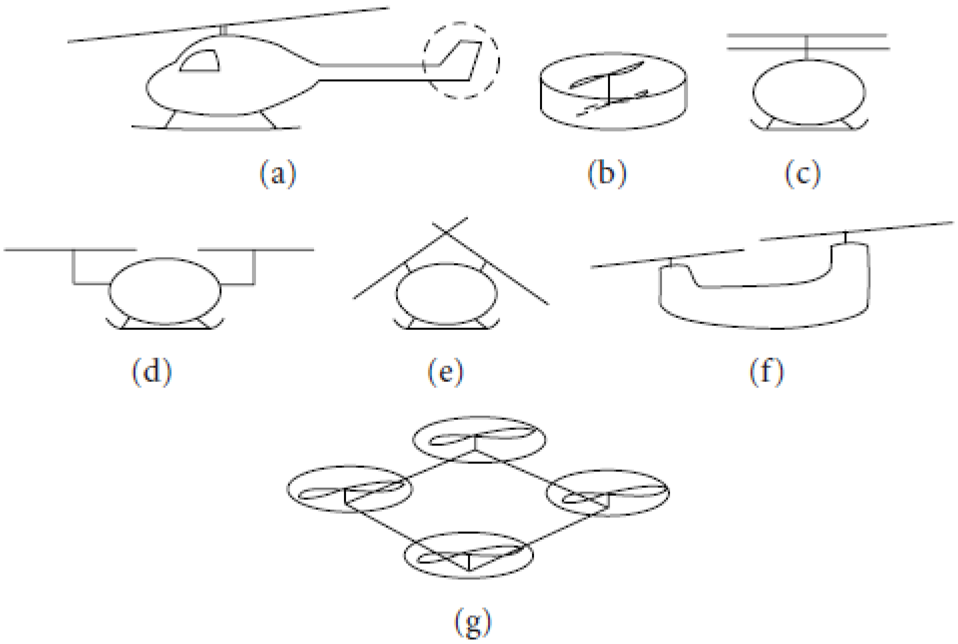

Figure 2. Graphic representation of rotary-wing configurations: (a) conventional configuration, (b) ducted coaxial, (c) conventional coaxial, (d) rotors side by side, (e) synchropter, (f) conventional tandem, (g) quad rotor [13].

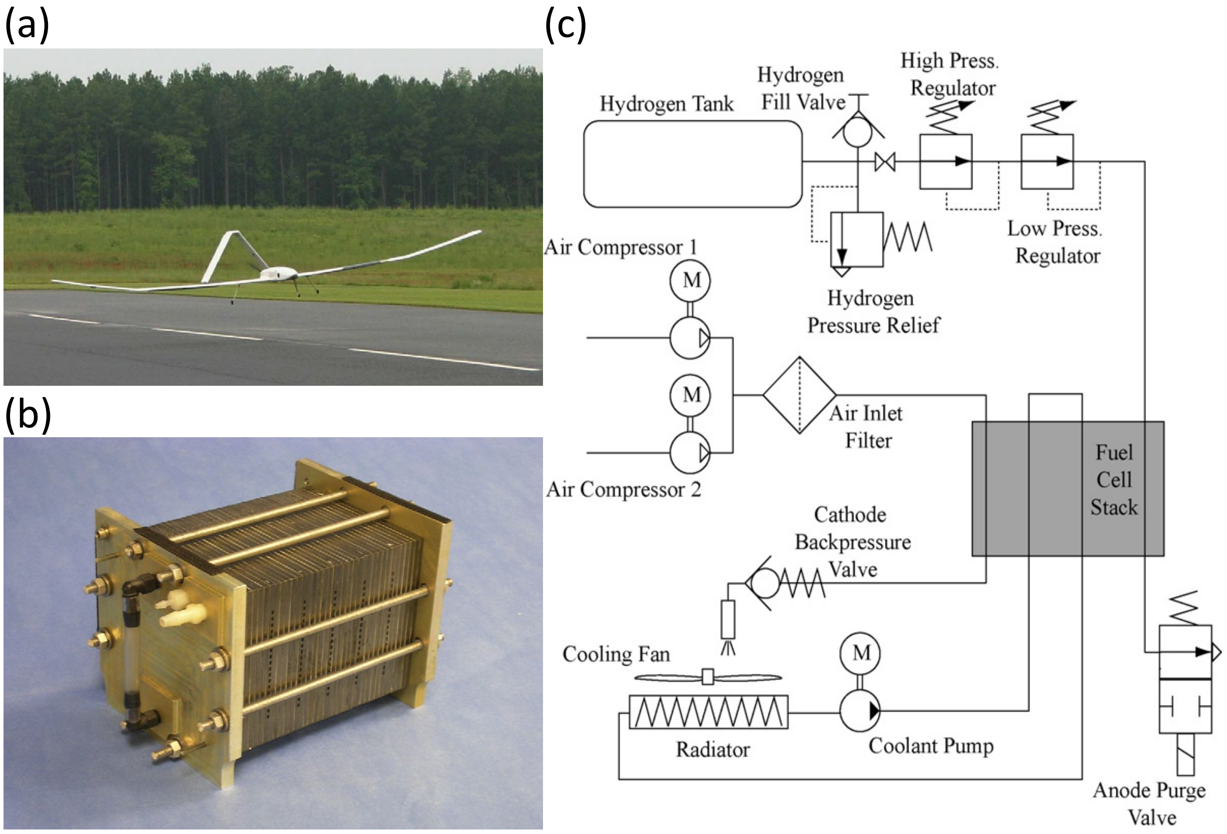

Figure 3. Schematic of (a) an aircraft in-flight, (b) a 32-cell fuel cell stack, and (c) system specifications [55].

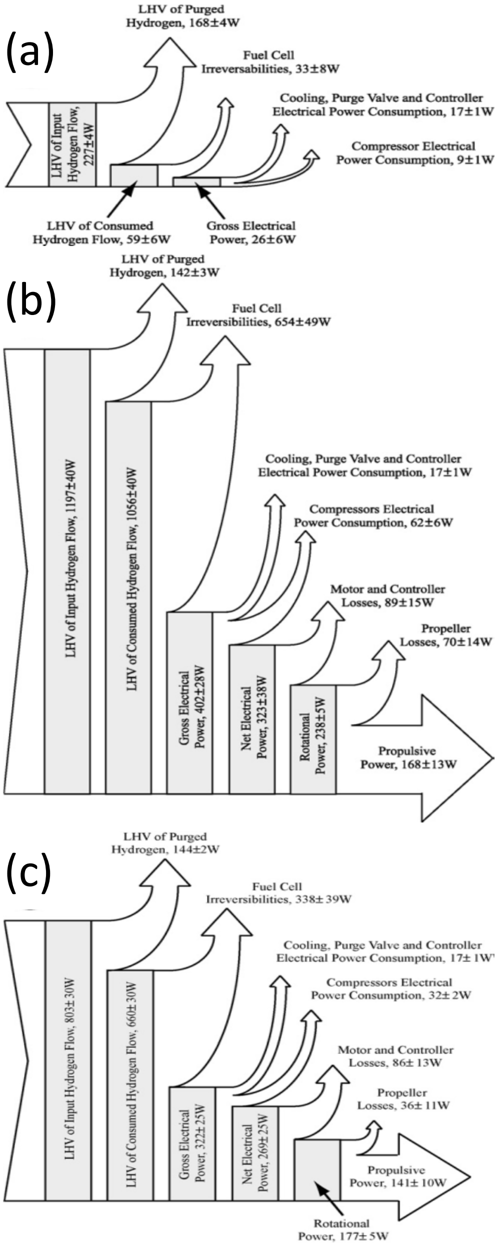

Figure 4. Sankey diagrams of (a) propulsion system losses at the idle condition, (b) propulsion system losses at the high power condition, and (c) propulsion system losses at the cruise condition [55].

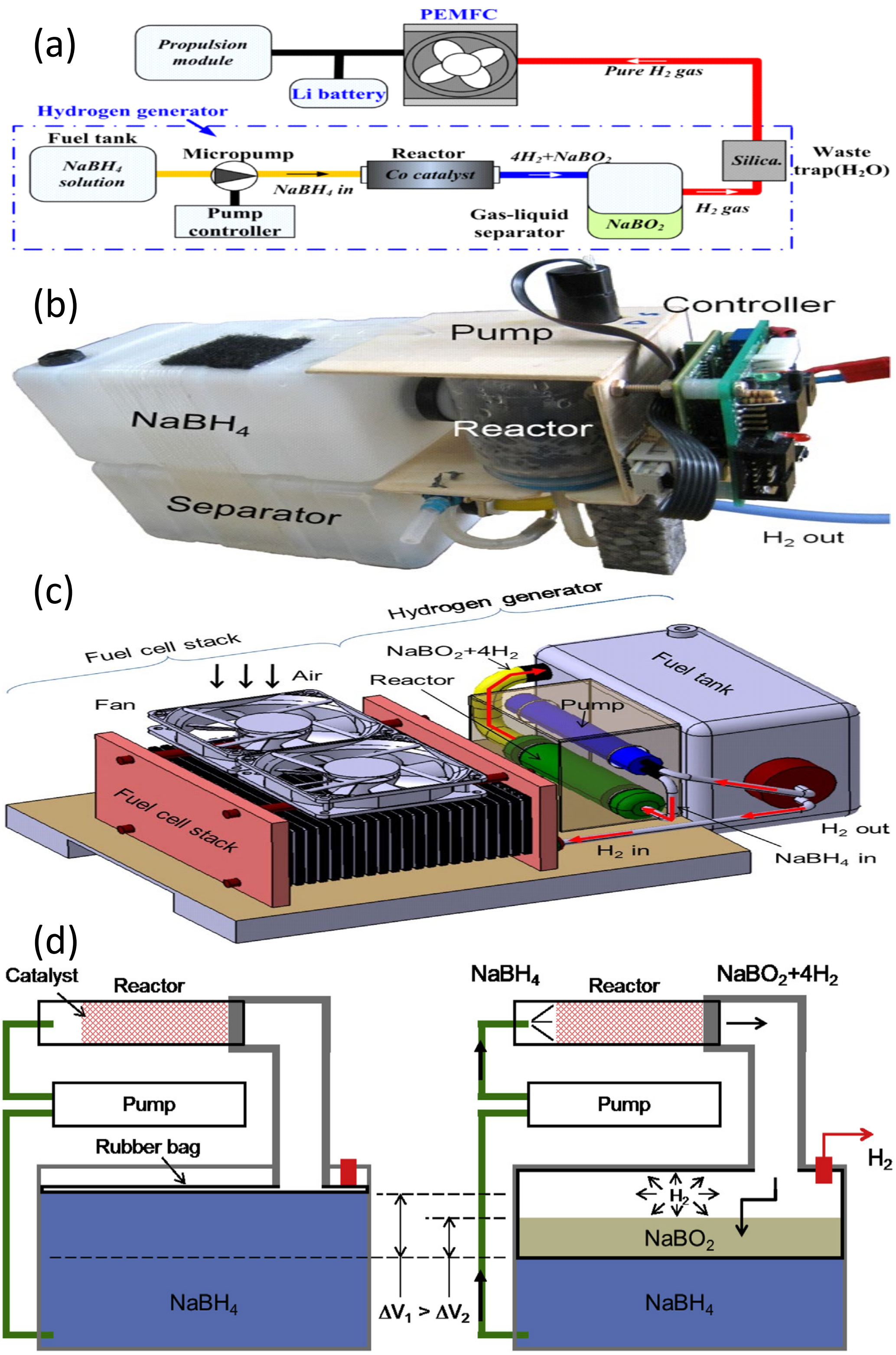

Figure 5. Schematic of (a) operating principle of fuel cell system [58] with (b) $NaBH_4$ hydrogen generator [59], (c) the fuel cell system consisting of a fuel cell stack and hydrogen generator, and (d) operation concept of a volume-exchange fuel tank [60].

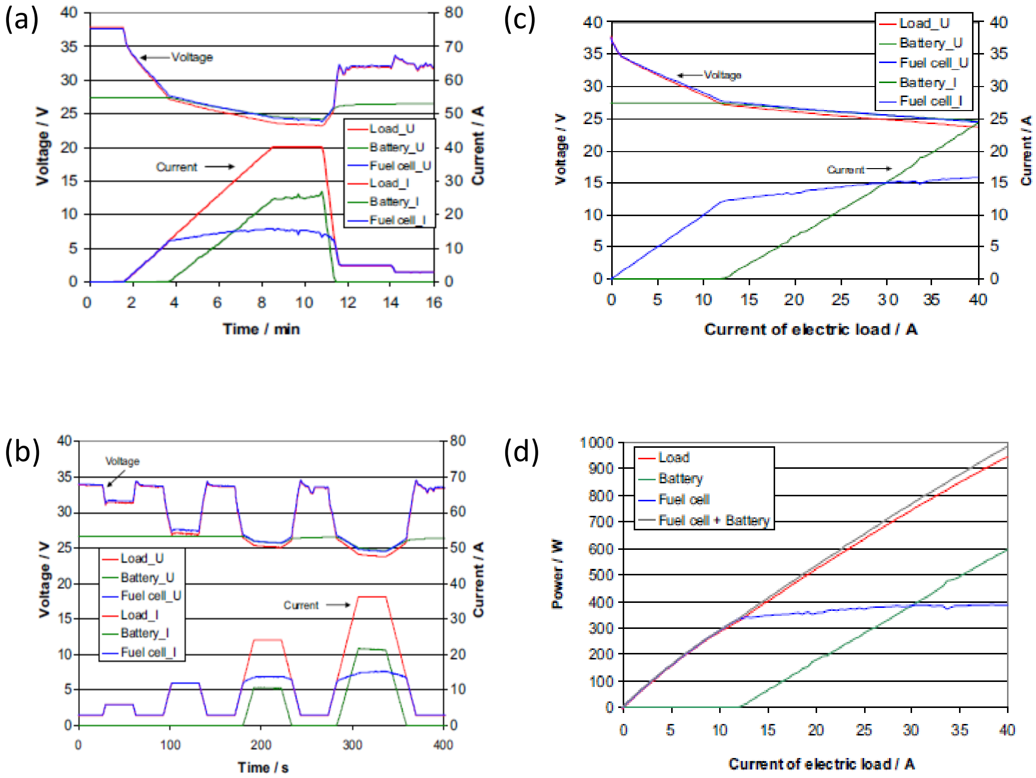

Figure 6. (a) Time traces of voltage and current for the hybrid system, (b) dynamic behavior of the hybrid system, (c) voltage and current variations, and (d) power variations [65].

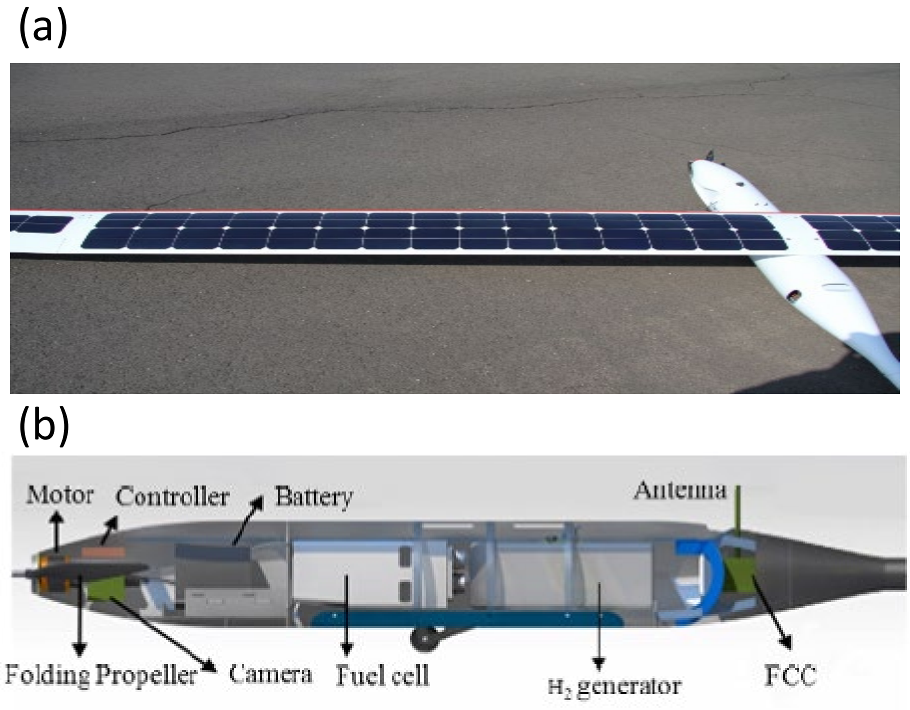

Figure 7. (a) Embedded solar cells wing, and (b) schematic of the layout of the EAV-2 [72]. Reproduced with permission from Springer.

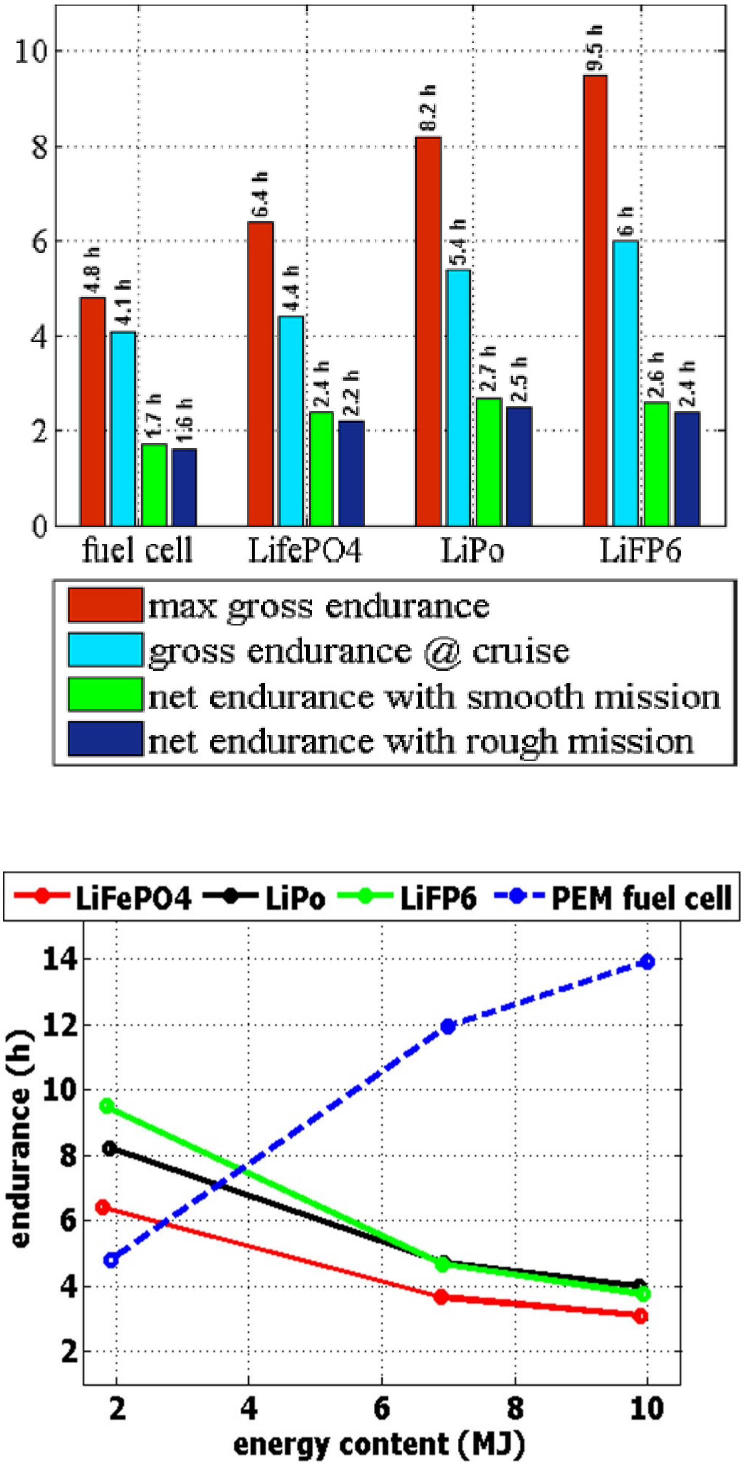

Figure 8. (a) Mission-based endurance with the initial energy content, and (b) gross endurance vs energy content obtained by changing empty mass and wing area [79].

Name	Weight (kg)	Payload (kg)	Specific energy (Wh/kg)	Max speed (m/s)	Lift to drag ratio	Altitude (m)	Endurance (h)	Ref
Black Widow MAV	5.65×10^{-2}	-	-	11.18	6.0	234.39	0.56	80
HEUAV	13.6	3	16.18	-	16.4	1525	20.4	81
−	16.4	-	7.1	14.5	-	10	0.72	55
-	12.5	-	124.9	-	24	-	24.1	82
Antex X02	10	4	-	41.94	-	-	0.8	83
Antex X03	100	30	-	36.11	-	-	0.3	83
Lusitania	10	5	-	41.67	-	-	0.8	83
Fling Wing	3	0.4	-	25	-	-	0.3	83
Silver Fox	12.2	2.27	-	56.39	-	-	10	83
Ion Tiger	16.10	2.27	447.21	14.07	17	-	24	84
-	580	-	156.25	-	-	-	-	85
-	2.2	-	-	9.8	-	23	-	60
300 W fuel cell	9.43	-	-	10.64	-	-	1.12	86
500 W fuel cell	12.16	-	-	12.46	-	-	0.72	86
800 W fuel cell	13.06	-	-	13.68	-	-	0.62	86
EAV-2	18	0.5	Solar cell: 51.13 Fuel cell: 92.86 Battery: 19.06	12.1	-	500	22.13	72
-	2.5	2	Fuel cell: 200	17	7.14	-	14.83	71
I	15.4	-	67.18	-	20	10000	-	87
II	6.21	-	166.44	-	20	10000	-	87
III	4.50	-	255.50	-	20	10000	-	87
IV	4.21	-	239.60	-	20	10000	-	87
-	14.2	2	Fuel cell: 63.38	17	20	Below 1000	4	17

			Battery: 12.96					
-	7.4	-	7.1	13.6	-	-	4.8	79

Table 1 Selected UAV performance reported in the open literature