Analysis of Output Power of Electric Unmanned Aerial Vehicle Hybrid Energy System Based on Temperature

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Abstract. The issue of energy and power systems is the main challenge faced by electric unmanned aerial vehicles for long endurance, and hybrid energy systems are the main way to solve the problem of electric unmanned aerial vehicles for long endurance. Under different operating temperatures, hybrid energy systems generate thermal losses and output power changes. This paper proposes an energy control process for hybrid energy systems based on thermal analysis and conducts simulation analysis. When the solar cell subsystem, fuel cell subsystem, and lithium battery subsystem operate at different temperatures, the flight duration of electric drones changes. The results show that under the operating temperature of solar cells at 25℃ and fuel cells at 66℃, electric drones can fly for 24 hours. When the temperature of the solar panel rises to 35℃ and the working temperature of the fuel cell is at 74℃, the hybrid energy system can only provide 18 hours of power due to changes in the working temperature of the electric drone, reducing the flight time by 6 hours.

Keywords: Electric UAV; Hybrid energy system; Output power; Temperature; Thermal analysis.

1. Introduction

The power supply technology of drone systems is one of the main issues in the development and research of drones [1], and hybrid energy systems are the development direction of drones for long endurance. The structure of hybrid energy systems has been widely proposed, such as the combination of hydrogen fuel cells and lithium-ion batteries [2], which comprehensively utilizes three types of energy sources: fuel cells, solar cells, and lithium batteries, configures corresponding energy management controllers, and analyzes the power generation characteristics of the system [1]. In 2010, the Illinois Institute of Technology proposed a hybrid energy system solution consisting of solar cells, rechargeable batteries, and fuel cells to improve the long endurance of unmanned aerial vehicles [3]. In 2012, Bohwa Lee from the Korean Aerospace Research Institute conducted research on hybrid unmanned aerial vehicles equipped with solar cells and batteries based on successful test flights of pure fuel cell unmanned aerial vehicles. He established solar cell, battery, and fuel cell models and conducted numerical simulations [4,5]. Hybrid unmanned aerial vehicles will become a cutting-edge research hotspot in the field of unmanned aerial vehicles.

The main role of energy management is to unify the management of electrical energy throughout the entire life cycle of the spacecraft during its flight phase, ensuring that it meets the energy needs of various flight missions of the spacecraft. The United States was the earliest country to conduct research on aircraft energy management technology. In the early 1970s, it proposed energy autonomous control electronic systems, becoming the embryonic form of energy management technology [6]. The energy management system was proposed by NASA research institutions in the 1980s. It mainly has functions such as fault diagnosis, isolation, and recovery of power supply and distribution systems, battery management, load priority management, and dynamic scheduling management of energy plans[7]. The research work on energy management in China started relatively late, mainly focusing on the preliminary exploration of the energy management system of China's space stations [8,9].

Based on the typical mission profile of electric drones, this article first analyzes the energy output and demand of the hybrid energy system of electric drones, and proposes an energy control process for the hybrid energy system based on exergy analysis. Then, the variation of the output power of the hybrid energy system with temperature was analyzed. Finally, the impact of temperature on the state and operating time of hybrid energy systems was analyzed using a typical mission profile of electric drones. The research results have important research value and application prospects for the energy system design of electric drones.

2. Energy output and demand analysis of hybrid energy systems

Based on the task profile power system demand information and energy system status information, control the power supply of each power subsystem, adjust the output voltage of each power supply, and adjust the output power to meet the requirements

$$P_{req} = P_d + P_{pld} = P_{sun} + P_{fc} + P_{bt} \quad (1)$$

Among them, P_d is the required power for the flight profile, P_{pld} is the power required for the avionics equipment.

In the mission profile of electric drones, a hybrid energy system is used to power them, with priority given to solar and fuel cell power supply, and lithium batteries as backup power sources. Due to changes in the working environment of electric drones, the output power of each battery subsystem fluctuates.

(1) For the solar cell subsystem, the output power will vary depending on the heat loss generated under different solar panel temperatures. The working temperature of solar panels is generally around 25℃. When the temperature increases, it will cause thermal damage and result in a decrease in output power. The general requirement is that the loss amount should not exceed 10% of the working output power at 25℃, that is, the working temperature of solar panels should not exceed 35℃ [10].

(2) For the fuel cell subsystem, the output power will vary depending on the heat loss generated at different fuel cell operating temperatures. When the working temperature of a fuel cell is around 70℃, the energy loss is minimal. When the temperature increases or decreases, it will cause energy loss and result in a decrease in output power. The general requirement is that the energy loss should not exceed 10% of the output power, that is, the operating temperature range of fuel cells is 60℃~75℃ [11].

(3) For the lithium battery subsystem, the output power will vary depending on the different losses generated under different operating temperatures of the lithium battery. When the working temperature of a lithium battery is around 30℃, the loss is minimal. When the temperature decreases, it will cause loss and decrease the output power. The general requirement is that the loss amount should not exceed 10% of the output power, that is, the operating temperature range of lithium batteries is -5℃~45℃ [12].

3. Output Power Analysis of Hybrid Energy Systems

The electric drone EAV-2 adopts a hybrid energy system composed of solar cells, fuel cells, and lithium batteries [10]. Under the conditions of light intensity and battery temperature, its relevant parameters are shown in Table 1, Table 2, and Table 3:

Table 1. Electrical Performance Index Parameters of Solar Cell Subsystem

Parameter	Peak power, W	Rated voltage, V	Rated current, A	Open voltage, V	Short current, A
Value	238	28.1	5.88	33.7	6.25

Table 2. Electrical Performance Index Parameters of Fuel Cell Subsystem

Parameter	Min power, W	Peak power, W	Max power, W	H_2 capacity, kg
Value	100	300	360	0.336

Table 3. Electrical Performance Index Parameters of Lithium Battery Subsystem

Parameter	Rated capacity, Ah	Nominal voltage, V	Nominal current, A	Initial SOC, %	SOC charge range
Value	4.3	25.9	2.3	100	0.2-0.9

According to the mission profile of the electric drone and the power supply strategy of the hybrid energy system, at the operating temperature of the solar cell of 25°C, it can provide 154W. When the temperature of the solar panel changes, the output power becomes

$$P_{sun,m} = 154 - \Delta I(T) \tag{2}$$

Similarly, when a fuel cell operates at a reference temperature of 66°C and a rated power of 300W, when the operating temperature of the battery changes

$$P_{fc,m} = 300 - \Delta I(T) \tag{3}$$

Lithium batteries will also undergo changes during charging and discharging. When discharging at a reference temperature, the output power is

$$P_{bt,out} = P_{req} - P_{sun,m} - P_{fc,m} - \Delta I(T) \tag{4}$$

When charging at the reference temperature, the charging capacity is

$$\Delta SOC_{in} = P_{in} - \Delta I(T) \tag{5}$$

Therefore, considering the influence of temperature, the flight time of unmanned aerial vehicles will be reduced.

4. Simulation analysis

4.1 Drone mission profile power demand parameters

Typical mission profiles of unmanned aerial vehicles include takeoff phase, climb phase, cruise phase, glide descent phase, landing deceleration phase, and deceleration run phase. The required power for the takeoff phase is 500W; The power consumed during the climb phase is 500W; Cruise phase, cruise power demand is 202W; The power system does not consume power during the glide descent phase, landing deceleration phase, and deceleration run phase.

The mission profile of an electric drone requires additional avionics equipment power, approximately 20W, in addition to the electrical power required for each stage of flight.

Set the takeoff date as the summer solstice, at 9:00 am, flying south from 40°N, with a ground temperature of 30°C. The cruise phase accounts for 99% of the entire flight time, and the takeoff and landing process time is relatively short. Therefore, when designing the hybrid energy system of electric unmanned aerial vehicles, the cruise state should be the main design point, and according to the design, the cruise duration is about 24 hours.

During the takeoff and flight process of the drone, the maximum required power is 520W, and the cruise phase takes up the main time, requiring a power of 222W [13].

4.2 Power distribution in hybrid energy systems

During the takeoff and flight process of the drone, the total required power is 520W, which requires three types of energy to be output simultaneously. The solar cell can provide 154W, and the fuel cell operates at rated power, with an output power of 300W. However, 66W is still needed, which is provided by lithium battery discharge.

During the deceleration landing phase of the drone, the sun has risen and solar cells can provide 20W of electricity required for all avionics equipment. At this point, the fuel cell does not work, and the excess electricity from solar energy charges the lithium battery.

The initial solar energy combined with lithium battery output can meet the cruise flight requirements of 222W, and the fuel cell is not working. When the lithium battery discharge reaches the required discharge depth of 0.2, the fuel cell is activated, and the electricity required for the drone is output by the combination of solar cells and fuel cells.

After the sun sets, the solar cells will no longer output electrical energy. Fuel cells are the main energy source for drones, and they mainly rely on fuel cells to power the drones at night. Until the next morning when the sun rises, the fuel cells run out of hydrogen storage during cruising, and the drones enter the landing process.

4.3 The Influence of Temperature on the Energy State of Hybrid Energy Systems

Figure 1 shows the changes in the state of the electric drone energy system over flight time, indicating that the states of various energy sources continuously change during the flight process. P_{sun} and $P_{\max}$ are the output power of the solar cell and the output power of the maximum light intensity received, respectively. After entering the landing phase, the output power of the solar cell can quickly charge the lithium battery to 90%, but the fuel cell energy has been exhausted, and the drone cannot continue to fly.

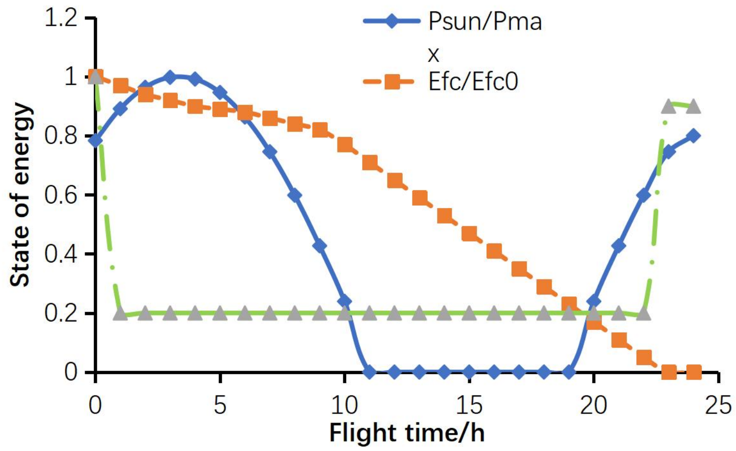

Fig. 1 Energy system status of electric drone during flight

When the operating temperature of solar cells, fuel cells, and lithium batteries changes, the output power of the solar cells will change. When the operating temperature of the solar cells is T1 (not the reference operating temperature T0), it will cause damage. When the lost energy is 10% of the output power, the output power change curve of the solar cells during drone flight is shown in Figure 2, and the output power will decrease.

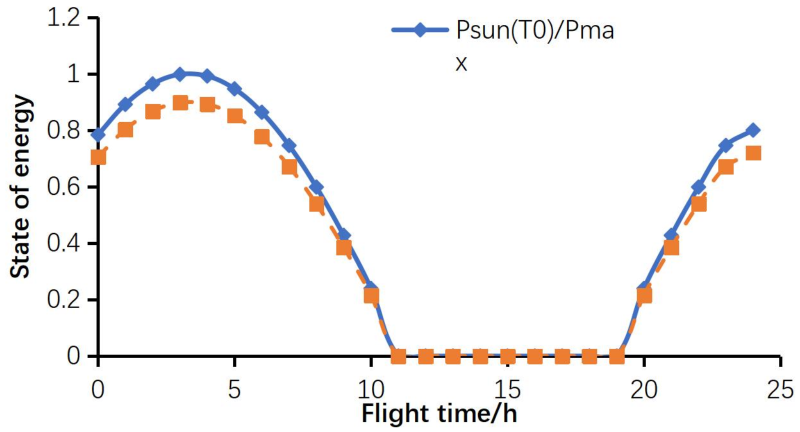

Fig. 2 Changes in energy status of solar cell at different temperatures with flight time

When the operating temperature of the fuel cell is T2, it will cause thermal loss. When the energy loss is 10% of the output power, the change curve of the fuel cell capacity during drone flight is shown in Figure 3, which will reduce the flight duration.

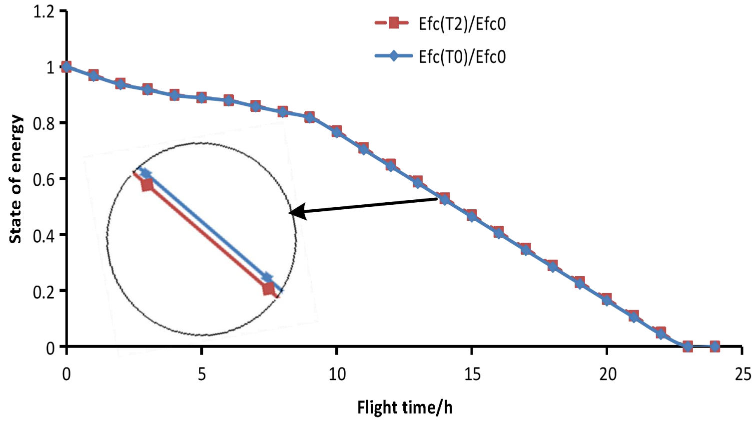

Fig. 3 Changes in energy status of fuel cell at different temperatures with flight time

When the working temperature of the lithium battery is T3, it will cause thermal loss. When the output power of the solar cell is used to charge the lithium battery, there will also be a partial loss of the energy charged into the solar cell.

4.4 The Effect of Temperature on the Flight Duration of Unmanned Aerial Vehicles

The electric drone adopts a hybrid energy system, and the designed flight time of the drone is about 24 hours when each battery subsystem operates at the reference temperature. During the takeoff and climb stages, the solar cell provides a power of 154W, the fuel cell operates at a rated power of 300W, and the lithium battery discharges at 66W. The operating time in this state is 5 minutes.

During the deceleration landing phase of the electric drone, the landing time is 9:00 on the second day, and the solar cells can provide 20W of electricity required for all avionics equipment. The fuel cells are not working, and the solar energy charges the lithium batteries with 134W of electricity until the lithium battery charging depth reaches 90%. This working time is 6 minutes.

The cruising flight requirement for electric drones is 222W, powered by solar cells and fuel cells, and operated for 10 hours under these conditions; When the sun sets at 19:00, only fuel cells provide electricity, and then work in this situation for 10 hours until 5am; When the sun rises, solar cells will provide electricity and work together with fuel cells until the fuel cell capacity is depleted, working for 4 hours.

Based on the above analysis, it can be concluded that each battery operates at a reference temperature, with a total flight time of 24 hours and 11 minutes. The total energy required for flight is

$$W = \left(\frac{520 \times 5}{60} + 222 \times 24 + \frac{20 \times 6}{60}\right) / 1000 = 5.38 kW \cdot h \tag{6}$$

The output power of solar cells is

$$W_{sun} = \int_{t_1}^{t_2} P_{sun}(t)dt = \left(\frac{154 \times (5 + 6)}{60} + 2173\right) / 1000 = 2.201 kW \cdot h \tag{7}$$

The output power of fuel cells is

$$W_{fc} = \int_{t_1}^{t_2} P_{fc}(t)dt = \left(\frac{300 \times 5}{60} + 2810\right) / 1000 = 2.835 kW \cdot h \tag{8}$$

The output power of the lithium battery is

$$W_{bt} = E_{bt} - SOC_H \cdot E_{bt} = 5.38 - 2.201 - 2.835 = 0.344 kW \cdot h \tag{9}$$

When the working temperature of a solar cell is between 25℃ and 35℃, its thermal loss varies linearly with temperature, i.e

$$\Delta I(T) = 1.467 \cdot T - 36.667 \quad (10)$$

As shown in Figure 4, as the temperature of the solar panel increases, the amount of electricity generated during the drone's flight will decrease. When the operating temperature is 35℃, the drone's flight duration will decrease from 24 hours to 21.5 hours.

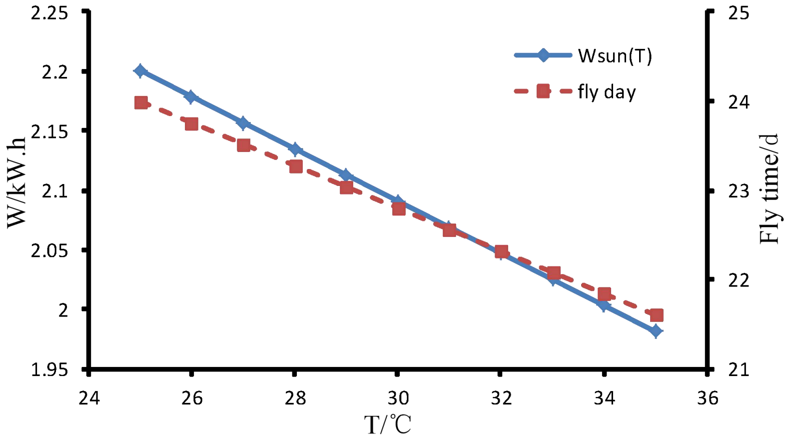

Fig. 4 Changes energy output and flight duration of solar panels at different temperatures

Similarly, when the operating temperature of a fuel cell is between 60℃ and 75℃, the variation pattern of fuel loss can be obtained as follows:

$$\Delta I(T) = 0.3033T^2 - 40.3000T + 1334.6700 \quad (11)$$

As shown in Figure 5, with different operating temperatures of fuel cells, the amount of electricity generated during drone flight will change. When the operating temperature is 74℃, the duration of drone flight will decrease from 24 hours to 20.5 hours.

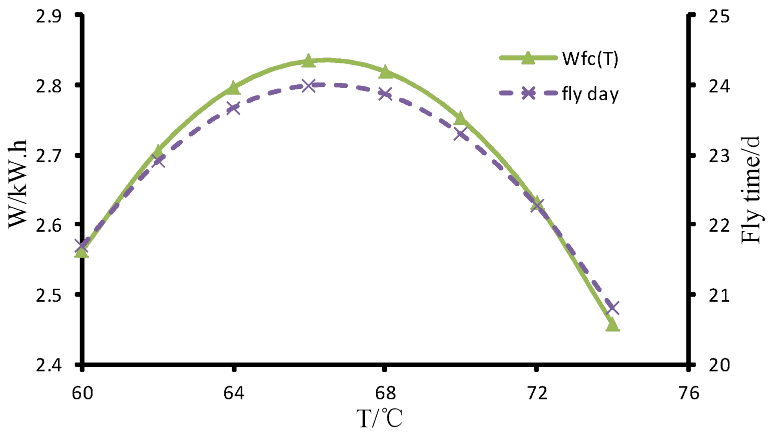

Fig. 5 Changes energy output and flight duration of fuel cells at different temperatures

Similarly, the charging and discharging process of lithium batteries can also cause energy loss, but generally at their operating temperature, the energy loss is very small, and solar cells generate sufficient power to meet the discharge and charging requirements of lithium batteries. Therefore, the main factors affecting the flight duration of drones are the temperature of solar panels and the operating temperature of fuel cells.

When the working temperature of the solar cell is 35℃ and the working temperature of the fuel cell is 74℃, the flight time of the drone is reduced to 18 hours, a total of 6 hours of flight time. Therefore, when the drone is executing the mission profile, it is necessary to monitor and control the working temperature of each battery in the drone hybrid energy system in order to enable the drone to successfully complete the flight mission.

5. Summary

this article analyzes the energy output and demand of the hybrid energy system of electric drones, and the variation of the output power of the hybrid energy system with temperature was analyzed. The results show that under the operating temperature of solar cells at 25°C and fuel cells at 66℃, electric drones can fly for 24 hours. When the temperature of the solar panel rises to 35°C and the working temperature of the fuel cell is at 74℃, the hybrid energy system can only provide 18 hours of power due to changes in the working temperature of the electric drone, reducing the flight time by 6 hours. The research results have important research value and application prospects for the energy system design of electric drones.

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