Available Energy Analysis of Electric Unmanned Aerial Vehicle Hybrid Energy System

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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. Under the power demand conditions of typical mission profiles of electric drones, this paper establishes an energy balance equation between the hybrid energy system power supply of electric drones and the power demand of drones. Considering the impact of operating temperature of each battery on power generation performance, a heat transfer model for solar cells, fuel cells, and lithium batteries was established. The heat transfer process of hybrid energy systems was analyzed. Based on the heat transfer model of hybrid energy systems, the heat transfer changes of solar cells, fuel cells, and lithium batteries were analyzed, and the heat transfer changes of hybrid energy systems were studied. The heat loss changes of each battery subsystem with operating temperature were given. The results show that the hybrid energy system has the best power generation performance at the reference temperature, and changes in operating temperature will cause thermal losses and reduce power generation.

Keywords: Electric drone; Hybrid energy systems; Energy balance; Exergy Analysis.

1. Introduction

Hybrid unmanned aerial vehicles will become a research hotspot and frontier in the field of unmanned aerial vehicles, and there is a large research space. In the development process of hybrid power, there are mainly the following key technologies: complex system modeling and simulation technology for hybrid unmanned aerial vehicles, energy control technology for hybrid unmanned aerial vehicles, trajectory planning and flight control technology based on energy optimization for unmanned aerial vehicles, low Reynolds number wing solar aerodynamic integrated design technology, and multidisciplinary design optimization technology for unmanned aerial vehicles[1].

In energy control technology, such as solar systems, their performance is influenced by factors such as lighting, aircraft attitude, altitude, and weather, which increases the complexity and control difficulty of hybrid systems. At the same time, the reliability of drones cannot be guaranteed. Therefore, the energy transfer characteristics of hybrid energy systems have become prominent, and the management technology of high-efficiency and high energy density energy systems has become a key and difficult issue in the research of hybrid energy system drones [2]. The energy transfer and conversion process of hybrid energy systems is influenced by multiple factors, and the available energy analysis method is used to analyze its process.

The exergy analysis method can be well applied to the energy transfer process and system optimization of the system, reflecting the energy utilization rate of the system. Feng et al. [3] conducted an exergy efficiency optimization analysis on the cooling, heating, and power equipment of the irreversible Brayton closed cycle power generation system, which has certain guiding significance for reducing irreversibility of the equipment. Chen et al. [4] used the finite time method to perform efficiency optimization analysis on the power generation system equipment of the closed Brayton thermal cycle, and discussed the optimal performance parameter design of each component. Kaushik et al. [5] summarized the energy and exergy analysis methods and systematically elaborated on the energy and exergy analysis process of power generation systems. Li Jing et al. [6] studied the energy and exergy changes of the Rankine cycle under different heat source conditions.

Fontalvo et al. [7] conducted an exergy analysis of a combination of power generation and cooling, providing ways to improve efficiency. Ö nder [8] used the exergy analysis method to analyze the utilization rate of organic Rankine cycle in waste heat utilization. It can be seen that energy analysis has been widely applied in energy systems, providing a theoretical basis for system performance and optimization.

Based on the typical mission profile of electric drones, this article first analyzes the energy balance equation between the hybrid energy system power supply of electric drones and the power demand of drones. Then, considering the power generation characteristics of each subsystem, a heat transfer model for solar cells, fuel cells, and lithium batteries was established, and the heat transfer process of hybrid energy systems was analyzed. Finally, the heat transfer changes of solar cells, fuel cells, and lithium batteries were analyzed, and the heat transfer changes of hybrid energy systems were studied. The heat loss changes of each battery subsystem with operating temperature were given.

2. Energy balance analysis of hybrid energy systems

2.1 Power supply requirements for typical mission profiles of electric drones

The typical mission profile of an electric drone is shown in Figure 1, which mainly includes the takeoff phase, climb phase, cruise phase, glide descent phase, landing deceleration phase, and deceleration run phase [9]. During the takeoff phase, the aircraft accelerates from a stationary acceleration to a takeoff speed and begins to climb. During the climb phase, climb to the cruising altitude of the aircraft at normal climb speed and angle of attack. During the cruise phase, at the predetermined cruise altitude, maintain horizontal flight while maintaining the same angle of attack and cruise speed. In the glide descent phase, when the remaining cruise energy reaches the minimum allowable value, it enters the glide descent state and flies to a safe altitude without power. In the deceleration phase of landing, use a smaller glide angle to glide, continuously reduce speed, and finally land. During the deceleration run, after landing, use an unpowered run to stop.

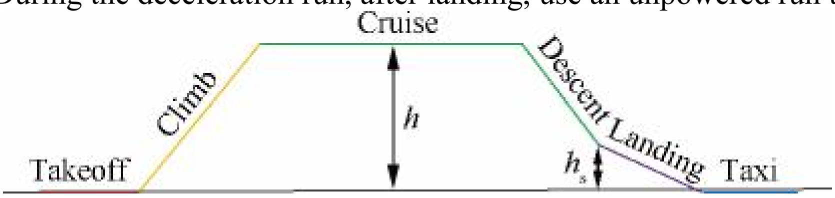

Fig. 1 Typical UAV flight profile

The demand for electricity for drones is related to the structural weight, power system weight, and carrying load weight of the aircraft. Meanwhile, the power consumption of electric drones varies during different flight stages. In a typical mission profile, the average power demand of an electric drone during takeoff is P_1 , the average power consumption during climb is P_2 , the average power consumption during cruise is P_3 , the average power consumption during descent and landing is P_4 , and the average power consumption during taxi is P_5 . Therefore, the power required for the entire mission process of the drone is:

$$W_{re} = \sum_{i=1}^{5} P_i t_i \tag{1}$$

Among them, P_i is the power of different stages and t_i is the flight time of each stage.

2.2 Energy balance analysis of hybrid energy systems

Electric drones require different power requirements for different flight postures in typical mission profiles. Considering the power loss P_{pld} of airborne equipment, it can be obtained that the required energy for flight of the entire machine is:

$$W_{tot} = \sum_{i=1}^{5} (P_i + P_{pld}) t_i \tag{2}$$

According to the energy sources of drones, they mainly come from solar cells, fuel cells, and lithium batteries. Lithium batteries have a charging and discharging process, which includes:

$$W_{tot} = E_{sun} + E_{fc} + [n \cdot (\eta_{dch} - \frac{1}{\eta_{ch}}) + 1] E_{bat} \tag{3}$$

Among them, the energy E_{sun} provided for solar cells, the energy E_{fc} provided for fuel cells, the initial capacity of lithium batteries is E_{bat} , η_{ch} and η_{dch} are the energy utilization efficiency during the charging and discharging process of lithium batteries, n is the number of charging and discharging times.

3. Available Energy Model for Hybrid Energy Systems

The hybrid energy system is an energy output mode that combines solar cells, fuel cells, and lithium batteries. According to the mission profiles of different stages, the takeoff and climb phases require a large amount of power, and three modes are used to output the energy together; Priority should be given to using solar cells in the cruise phase, and fuel cells should be used in the event of insufficient power supply from solar cells. Lithium batteries should be used as auxiliary energy throughout the entire process. The gliding phase, deceleration phase, and landing phase require less energy, and solar cells, fuel cells, and lithium batteries can be combined arbitrarily based on their power level.

Solar cells use the intensity of sunlight to convert solar radiation energy into usable electrical energy. During the utilization process, they are affected by factors such as environmental temperature, geographical location, and solar panel structure. The energy transferred is partially utilized, and the usable energy is represented by exergy. The unusable energy is called exergy loss. At the same time, there is a problem of energy loss due to the limitations of the system structure during the energy transfer process[10]. Considering the actual temperature and reference temperature, actual radiation intensity and reference intensity, the volt ampere characteristic curves of solar cells are different under different solar irradiance intensities and solar cell temperatures, and are also affected by environmental humidity, dust, and meteorological conditions. Considering the overall situation, consider solar cells as an energy closed system, where the input energy is solar energy and the output energy is electrical energy used by unmanned aerial vehicles. There are losses in the energy conversion process, including the energy lost by solar energy during the system conversion process, energy loss affected by environmental climate, and energy loss caused by MPPT controllers. According to the law of energy conservation, the system energy is expressed as:

$$P_{sun} = E_{Qs} = Q_{sun} - I_{ss} - I_{wth} - I_{mppt} \tag{4}$$

Among them, P_{sun} is the electrical energy output by solar cells, E_{Qs} is the available energy of solar cells, Q_{sun} is the solar radiation energy, I_{ss} is the lost energy of solar energy, I_{wth} is the energy loss caused by environmental and climate impacts, and I_{mppt} is the energy loss caused by the MPPT controller control process.

Consider a fuel cell as an energy stable flow system, where the input energy is the chemical energy carried by the fuel and the output energy is the electrical energy used by unmanned aerial vehicles. There are losses in the energy conversion process, including the energy carried away by the products generated during the system conversion process and the energy lost (some of the energy is taken away by the actively cooled coolant) [11]. According to the law of conservation of energy, given a reference temperature, the transfer equilibrium equation can be expressed as:

$$E_{H2} + E_{O2} = P_{fc} + E_{H2O} + E_{coolant2} - E_{coolant1} + I_{dis} \tag{5}$$

Among them, E_{H2} and E_{02} are the chemistry of hydrogen and oxygen, E_{H20} is the chemistry of the product water, $E_{coolant2}$ and $E_{coolant1}$ are the exergy quantity of coolant at the outlet and inlet, and I_{dis} is the loss of heat dissipation.

The electrochemical reaction generated by collecting electrons of the lithium batteries at the negative electrode is called polarization internal resistance, and during charging, the lithium ions reach the double electron layer of the negative electrode for oxidation reaction. The generated internal resistance is called tolerance internal resistance. Ohmic internal resistance generates Joule heat, polarized internal resistance generates polarization heat, and at the same time, chemical reactions are accompanied by reaction heat [12]. Under the influence of environmental conditions, the charging and discharging energy equation of lithium batteries will change under changes in temperature and humidity. Based on a certain reference temperature, the equilibrium equation can be established, which can be expressed as

During charging:

$$P_{in}(T) = \Delta SOC_{in}(T) + I_r(T,T_0) + I_j(T,T_0) + I_p(T,T_0) \tag{6}$$

During discharge:

$$\Delta SOC_{out}(T) = P_{out}(T) + I_r(T,T_0) + I_j(T,T_0) + I_p(T,T_0) \tag{7}$$

Among them, $I_r(T,T_0)$, $I_j(T,T_0)$ and $I_p(T,T_0)$ are the exergy losses compared to the reference temperature and actual temperature, respectively.

According to the above analysis, when the lithium battery of the hybrid energy system discharges to the drone:

$$P_{load} = P_{sun} + P_{fc} + P_{out} \tag{8}$$

Among them:

$$\begin{cases} P_{sun} = Q_{sun} - I_{ss} - I_{wth} - I_{mppt} \\ P_{fc} = E_{H2} + E_{02} - (E_{H20} + E_{coolant2} - E_{coolant1} + I_{dis}) \\ P_{out} = \Delta SOC_{out}(T) - [I_r(T,T_0) + I_j(T,T_0) + I_p(T,T_0)] \end{cases}$$

When solar cells and fuel cells in hybrid energy systems charge lithium batteries:

$$P_{load} = P_{sun} + P_{fc} - P_{in} \tag{9}$$

Among them:

$$\begin{cases} P_{sun} = Q_{sun} - I_{ss} - I_{wth} - I_{mppt} \\ P_{fc} = E_{H2} + E_{02} - (E_{H20} + E_{coolant2} - E_{coolant1} + I_{dis}) \\ P_{in} = \Delta SOC_{in}(T) + I_r(T,T_0) + I_j(T,T_0) + I_p(T,T_0) \end{cases}$$

4. Exegy Loss Law of Hybrid Energy Systems

From the above analysis, it can be concluded that the hybrid energy system of unmanned aerial vehicles composed of solar cells, fuel cells, and lithium batteries is affected by environmental factors during the power supply process, resulting in energy loss during the energy conversion process.

The absorption of heat by solar panels increases their temperature, which in turn affects the efficiency of thermoelectric conversion and leads to a decrease in output power. When the temperature rises from 25 ℃ to 60 ℃, the output power of solar panels decreases by 25%, manifested by the environmental and climatic impact of solar cells [13]. Therefore, it is the energy loss caused by environmental and climate impacts, and as the temperature changes.Due to the influence of environmental temperature, the output power decreases, resulting in a loss that approximately linearly varies with temperature, i.e

$$\Delta I(T) = aT + b \tag{10}$$

By fitting, the variation pattern of thermal loss can be obtained between 25 ℃ and 60 ℃

$$\Delta I(T) = 1.467 \cdot T - 36.667 \tag{11}$$

Due to the influence of battery temperature, changes in fuel cell performance will result in energy loss. Assuming that the reference temperature for fuel cell operation is, as the temperature changes, it will cause energy loss, which can be expressed as

$$\Delta I(T) = aT^2 + bT + c \tag{12}$$

Under the conditions of a single fuel cell current of 5A and an output power of approximately 130W, the variation pattern of fuel loss can be obtained within the range of fuel cell temperature from 310K (37 ℃) to 360K (87 ℃) [14]

$$\Delta I(T) = 0.3033T^2 - 40.3000T + 1334.6700 \tag{13}$$

Due to the influence of battery temperature, the performance of lithium batteries will change, resulting in changes in battery capacity and internal resistance, resulting in energy loss. As the temperature changes, it will cause thermal loss, which can be expressed as

$$\Delta I(T) = e^{-aT+b}q_{bt} + c \tag{14}$$

Assuming that the lithium battery subsystem of an electric drone operates under rated operating conditions at a reference temperature of 25 ℃ and has a discharge capacity of, the variation pattern of battery loss can be obtained within the range of -25 ℃ to 45 ℃ operating temperature of the lithium battery [15]

$$\Delta I(T) = e^{-0.0879T-2.8780} \cdot q_{bt} - 0.0063 \tag{15}$$

The hybrid energy system of the electric unmanned aerial vehicle EAV-2 [13], under the conditions of light intensity and battery temperature, has the relevant parameters of its solar cell subsystem as shown in Table 1.

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

The relevant parameters of the fuel cell subsystem of the electric drone EAV-2 are shown in Table 2.

Table 2. Electrical Performance Index Parameters of Fuel Cell Subsystem

Parameter	Min power, W	Peak power, W	Max power, W	H2 capacity, kg
Value	100	300	360	0.336

The relevant parameters of the lithium battery subsystem of the electric drone EAV-2 are shown in Table 3.

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 hybrid energy system of EAV-2 electric unmanned aerial vehicle, the changes in thermal losses caused by temperature changes during the operation of the solar cell subsystem, fuel cell subsystem, and lithium battery subsystem are shown in Figure 2.

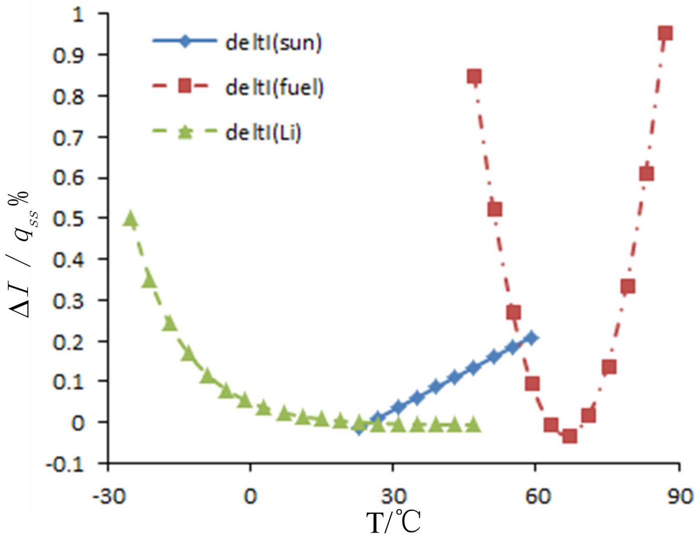

Fig. 2 Temperature dependent changes in exergy losses of solar cell subsystems, fuel cell subsystems, and lithium battery subsystems

According to the specific mission profile of the drone, during the operation of solar cells, as the temperature of the panels increases, energy loss will increase, resulting in a decrease in their conversion efficiency. Generally, solar cells operate at around 25 ℃; Fuel cells typically operate at around 70 ℃ due to their increased wear and tear at both high and low temperatures; Lithium batteries in low-temperature environments can cause internal chemical reactions to lag, increase internal resistance, and thus increase electrical losses, typically operating between 25 ℃ and 35 ℃.

5. Summary

Under the power demand conditions of typical mission profiles of electric drones, this paper establishes an energy balance equation between the hybrid energy system power supply of electric drones and the power demand of drones. The available operation temperature of solar cells is about 25 ℃. Fuel cells typically operate at around 70 ℃ and Lithium batteries typically operating between 25 ℃ and 35 ℃. The results show that the hybrid energy system has the best power generation performance at the reference temperature, and changes in operating temperature will cause thermal losses and reduce power generation.

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