System Analysis of the Drone with FC Battery Fueled by Bio-hydrogen

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The use of drones in logistics is accelerating. However, there is a problem with the duration of batteries in that the capacity is insufficient. Owing to this, a serious problem would be caused by an expansion of the delivery area. Manufacturers of batteries are trying to increase the capacity, while global-warming protection is necessary. Thus, renewable energy and/or the more-efficient batteries, such as the fuel cell (FC) battery, are promising countermeasures. In this research, an FC battery fueled by Bio-H₂ from biomass feedstock was investigated. Using the demo drone, the Li-ion battery and FC battery were compared in terms of the eco-burden on the basis of a life cycle assessment approach. Here, through flight tests, the relationship between output and payload was evaluated. Then, with the FC battery with storage mounted on the drone, the performance was evaluated. The FC battery bearing the storage carries, metal hydride, is still under developing toward improving the performance.

1. Introduction

Biomass is attracting attention as a new energy that considers the environmental impact. Hydrogen obtained from biomass feedstock through the gasification process, known as Bio-H₂, is eco-friendly, and it is possible that it can be used for fuel cells (FCs). A drone is a type of unmanned aerial vehicle (UAV). A rotor wing is mounted, and the rotary-wing machine
faces the rotor facing upward and supports total weight of the fuselage with its thrust. The drone market is expanding each year in Japan. The market size of UAVs is expected to reach 18.6 billion yen in 2020 from about 5 billion yen in 2017. Particularly, as an application of various forms of drone, their use for logistics is sought at the Ministry of International Trade and Industry and the Ministry of Land and Infrastructure. Battery capacity will be expanded to respond to the expansion of the delivery area caused by the increase in the number of courier services handled. Tseng et al. conducted empirical studies to model the energy consumption of drones in consideration of various flight conditions and payloads. They also built a further flight tour plan by optimizing charging for drone missions by accurately modeling the battery performance in each scenario. By introducing the FC system using Bio-H₂ in logistics, we aim to reduce the environmental burden and realize long-term unmanned operation.

Currently, compression tanks (70 MPa) are mainly used for hydrogen fuel storage, including fuel cell vehicles (FCVs). However, it is difficult to reduce the environmental impact, because it is necessary to use a large amount of energy to compress hydrogen up to 70 MPa. Considering the necessity of long-distance operation, using large-capacity hydrogen storage metal hydride is being considered. Metal hydride is an intermetallic compound composed of a combination of an element (A) that reacts with hydrogen to form a hydride and an element (B) that hardly reacts with hydrogen. The hydrogen content per volume (kg/L) of metal hydride is higher than that of a high-pressure tank (70 MPa). For operation at room temperature and normal pressure from the viewpoint of mounting on a drone, we used a lanthanum misch alloy (LaNi₄₋₁₂ Mn₀₁₂ Al₀₁₄). The hydrogen occlusion/release temperature of the metal hydride was 303 K, and both occlusion pressure and discharge pressure were 0.4 MPaG or less. Moreover, because the effective hydrogen content is about 1 mass%, the energy density per volume was higher than that of the high-pressure tank. For cost reasons, misch metal was used, so purification costs can be reduced compared with pure lanterns, and impurities are eliminated compared with other alloys. It is also useful for the purification of Bio-H₂ when it is used in a polymer electrolyte membrane fuel cell (PEMFC). From the above, it can be seen that there is a possibility of use in mobile equipment.

In this study, we tried balancing thrust and gravity while holding payloads of various weights to obtain the weight and power consumption of a FC that can be installed. Further, we performed life cycle assessment (LCA) on the batteries to be mounted and compared the discharged greenhouse gas (GHG) at the manufacturing phase of the battery. In addition, we compared the time of flight with the environmental impact.

2. Experimental

2.1 Power consumption for drone hovering

To investigate the weight of the installable FC system and the required power consumption, a hovering equation of equilibrium and two aerodynamic models were used. The specifications of the drone and battery used in this study are shown in Table 1.

In measuring the power consumption of each installed payload, experiments were conducted to balance the weight and thrust (see Fig. 1).

In Fig. 1, $W_{\text{drone}}$, $g$, $T$ and $S$ are the total weight of a drone [kg], the gravitational acceleration [m/s²], the thrust power (lift power) [N], and the tensile force of fixed strings [N], respectively. The balance equation for a vertical direction is expressed as Eq. (1).

$$T = W_{\text{drone}}g + \sum_{i=1}^{4} S_i \sin \theta$$

In the model between the lift power and power consumption of a drone, the following two simple physical models were considered. One is based on momentum theory, and the relationship between the lift power of the disk and the flow rate of air can be determined from the rotary action of the blades (see Fig. 2).

$$T_{\text{theoretical}} = 2\pi \rho R^2 v^2$$

where $R$, $v$ and $\rho$ are the disk radius of the blade [m], the rate of blow-down at the hovering flight [m/s], and air density [kg/m³], respectively. According to Fig. 2, although

| Specifications of the drone |
|-----------------------------|
| Motor and body (carrier) | 0.84 kg |
| Battery (lithium ion) | 0.18 kg |
| Power meter | 0.08 kg |
| Data logger | 0.05 kg |
| Dimension | 489.44 mm × 392.48 mm |
| Battery | 3500 mAh, 11.1 V |
| Motors | kV: 1000 rpm/V(× 4) |

Fig. 1 Schematics of measurement of the thrust power
Theoretical must consider the air speed at the elevation \((v \text{ [m/s]})\). \(v\) was assumed to be 0 in this study, because this energy estimation was focused on the hovering flight only. Moreover, \(v = 6.8 \text{ m/s}\) was adopted as a constant value based on the measurement result. Note that, \(T_{\text{theoretical}}\) was approximately calculated to consider \(S\) in each case of payload.

Next, another model suggested by Baluta was used as well. It considers an infinite-length cylinder with a cross section of the blade disk. That is, based on the momentum conservation law, it is known that the force \(T \text{ [N]}\) acting on a substance is equal to the rate of change of momentum in a certain time. Hence, the rated battery power \(P \text{ [W]}\) is estimated by Eq. (3).

\[
P = \sqrt{\frac{T^2}{2\pi \rho R^2}} \tag{3}
\]

### 2.2 Environmental impact assessment

In this research, LCA is used to evaluate the environmental impact of each battery, especially \(\text{CO}_2\) emission. In this study, both the indirect emissions of the manufacturing phase and the direct ones of the use phase were evaluated.

In the manufacturing phase, the emissions covered the components (materials), battery assembly, etc. In the use phase, the emissions were estimated in comparison with the differences of types of battery and performance. The system boundary is shown in Fig. 3. The sub-process shown by the dotted line was not treated because of the difficulties of detailed data acquisition.

Considering the capacity of each battery, the functional unit was set to the performance index in each battery \((\text{PI} \text{ [kg·min]})\), which is defined by the following methodology.

The carrier weight except the weight of the battery \((W_{\text{carrier}} \text{ [kg]})\) and the \(i\)-th battery weight \(W_{\text{battery}} \text{ [kg]}\) \((i = 1: \text{Li-ion}, 2: \text{FC})\) are

\[
W_{\text{carrier}} = W_{\text{carrier}} + W_{\text{battery}} \tag{4}
\]

Considering the balance of the lift capability of \(T \text{ [N]}\) and the net weight of the drone, the payload in each battery is

\[
\text{Payload} = \frac{T(P)}{g} - (W_{\text{battery}} + W_{\text{carrier}}) \tag{5}
\]

where \(T(P) \text{ [N]}, \text{Payload, [kg]},\) and \(g \text{ [m/s²]}\) are the lift capability of \(P \text{ [W]},\) the payload of the \(i\)-th battery, and gravitational acceleration, respectively.

Next, the \(i\)-th flight duration \((\text{Fdi} \text{ [min]})\) is calculated as expressed in Eq. (6) using the \(i\)-th net battery capacity \(C_i \text{ [Wh]}\).

\[
\text{Fdi} = \frac{60C_i}{P} \tag{6}
\]

Based on these equations, the performance index \((\text{PI} \text{ [kg·min]}\) in each battery is defined as Eq. (7).

\[
\text{PI} = \text{Payload} \times \text{Fdi} \tag{7}
\]

In addition, assuming the lifetime of the drone, the indirect emissions per flight duration can be estimated. For instance, if the lifetime is \(LT \text{ [h]}\), the flight number \((\text{Fn} \text{ [-]}\) for \(LT \text{ [h]}\) is

\[
\text{Fn} = \frac{60LT}{\text{Fdi}} \tag{8}
\]

Therefore, the indirect emission per flight duration is obtained by dividing the total indirect emissions by \(\text{Fn}\). The indirect emission is limited to the battery device only.

Background data during the manufacturing phase was acquired from the Ecoinvent 3.0 database using SimaPro (v.8.3.0.0), and ReCiPe Midpoint (v.1.13) was used. Inventory data for FC and Li-ion batteries were collected from an Outcome report \(^9\) and Espinosa et al. \(^10\) in weight ratio as a component of the battery in this study. As for the use phase, the GHG of each battery is approximated by using the fuel storage amount and the emission intensity of each fuel. Here, the GHG emissions in the use phase \((E_{\text{em,kg-CO}_2/kg\text{-min]}})\) are evaluated by the following formulas using the emission factor \(\alpha \text{ [kg-CO}_2/kWh]\), which is the emission of the general grid in Tokyo, Japan \(^11\) and the
specific factor of Bio-H₂, \( \beta [\text{kg-CO}_2\text{eq/NL}] \) — see Eqs. (9) and (10).

\[
E_{\text{Li-ion-use}} = \frac{\alpha C_{\text{Li-ion}}}{1000P_{\text{Li-ion}}}
\]

(9)

\[
E_{\text{FC-use}} = \frac{\beta C_{\text{FC}}}{1000\eta P_{\text{FC}}}
\]

(10)

Note that \( \eta \) in Eq. (10) is a discharge efficiency. This means that \( E_{\text{FC-use}} \) is counted for the total H₂ fuel stored.

3. Results and Discussion

3.1 Performance of a drone

Next, through our performance experiments, the relationship between the thrust power (lift power) and the rated power was determined and is illustrated in Fig. 4.

In Fig. 4, by varying the total weight, the rated power was measured. In this experiment, the power was supplied from the outboard. The experiments were executed in the room. The ambient temperature was room temperature. In practical use, the temperature is lower and the performance is affected by the condition. Thus, the influence of temperature will be investigated in the future.

The total weight control was carried out using various weights. The measurement results were plotted along the theoretical curve as above. In this study, considering the scale of the FC that will be carried on the drone and the specification of the experimental drone, the rated power of 300 W (= \( P \)) was simulated. The rated power of Li-ion had the same condition as the FC battery. From Fig. 4, the drone cannot lift at a larger range than 26.65 N (the dotted line). That is, the maximum allowance of the FC battery and a carrier would be approximately 2.7 kg theoretically. In this study, based on the experimental results, 21.29 N at a rated power of 311 W was adopted because of the scale of the FC battery (300 W) used in the experiment. This maximum allowance was 2.17 kg. However, the thrust power gains exponentially by increasing the power from the battery. This implies that the larger scale of the FC battery obtains greater benefit, even if the total weight of the FC battery is somewhat heavy. This means that both the expansion of flight duration and a more beneficial payload can be achieved.

3.2 Environmental impact

The environmental impact of the FC battery was analyzed. In this study, the FC battery consisted of an FC device and storage using metal hydride. The specification of this system is shown in Table 2.

Based on this specification, the GHG emissions were estimated as shown in Fig. 5. The loading weight of the metal hydride, which is the main influence on the total weight, was considered.

Fig. 5 shows the LCA result (manufacturing phase) of each battery. The indirect emissions are \( 2.81 \times 10^3 \) kg-CO₂eq./kg-min for the Li-ion battery and \( 4.17 \times 10^3 \) kg-CO₂eq./kg-min for the FC battery.

Table 2 Specifications of each battery

| Battery type | Li-ion | FC |
|--------------|--------|----|
| Battery weight \( W_{\text{Li-ion}} \) | 0.18 kg | Stack : 0.80 kg |
| Payload \( \text{Payload}_{\text{Li-ion}} \) | 1.16 kg | Solenoid valve etc : 0.30 kg |
| Capacity \( C_{\text{Li-ion}} \) | 0.021 kWh | Metal hydride : 0.10 kg |
| Payload \( \text{Payload}_{\text{FC}} \) | 0.08 kg | Cartridge (storage) : 0.06 kg |
| Capacity \( C_{\text{FC}} \) | Discharged volume : 14.96 NL | \( \eta \) (Discharge eff.)=91% |

Note: Carrier weight \( (W_{\text{carrier}}) = 0.84 \) kg (see Table 1), rated power \( (P) = 300 \) W.
CO2eq./kg·min for the FC battery. This implies that the emissions of the FC are more affected than those of the Li-ion battery. In the case of the Li-ion battery, aluminum was used for the parts of package, and the battery was the dominant influence on the total emissions. However, the platinum used as a catalyst, whose weight was only 0.32% of the total weight, accounted for 68% of the total emissions (see Fig. 6). This result is an important indicator for the design of FC battery to mitigate the environmental impact.

Next, regarding the direct emissions of the use phase, the performances of the drone, that is, the flight duration and the payload, were extremely significant. Therefore, based on the power consumption of the Li-ion battery or the FC battery, the emissions were estimated. In the FC battery, a flight duration of $F_d_{FC}$ was obtained by dividing the discharged volume [NL] at the flow rate of 3.6 NL/min for operation of 300 W. The specific CO2 emissions of fuel are shown in Table 3. In this study, as reference data, the H2 of fossil fuel origin was estimated too (see Table 3). In Table 3, “SMR” means the H2 derived from steam methane reforming, which is generally used for FC devices. The environmental aspects were estimated in comparison with Bio-H2 and the conventional H2 of fossil fuel origin.

As shown in Fig. 7, the FC using Bio-H2, whose specific emission has a characteristic of negative emission, can be greatly mitigated in comparison with the Li-ion battery.

Finally, the integrated GHG emissions of the indirect and direct ones were evaluated (see Fig. 8). In this estimation, the lifetime of the drone LT [h] is necessary. Here, the lifetimes of both batteries (LT) are assumed to be 2000 h. The LT was referred to that of a nonstationary battery.

In our LCA, the GHG emissions of each battery would be more eco-friendly if eco-fuel were used, even if the fuel consumption depends on the operating condition of the drone. Regarding the eco-burden in the manufacturing phase, improvements of performance are necessary. This time, the influence of GHG emissions was small. However, in the other impact categories, there are indices whose effects cannot be ignored (e.g., abiotic depletion potential). For these problems, for instance, the expansion of flight duration would be necessary. The choice of suitable metal hydride is the most important issue. Metal hydride with more adsorption efficiency is required. The reduction weight of the FC device must be considered too. In this study, the weight of the FC device was most affected. Thus, appropriate design of the FC device for drone operation is necessary. Soon, the evaluation of a suitable choice of metal hydride will begin. In our study, the environmental impacts are $2.1 \times 10^{-3}$ kg-CO2eq./kg·min for the Li-ion, $-5.3 \times 10^{-2}$ kg-CO2eq./kg·min for the FC.
CO$_2$ eq./kg-min for the FC using Bio-H$_2$, and $3.9 \times 10^{-2}$ kg-CO$_2$ eq./kg-min for the conventional H$_2$ fuel. The FC using hydrogen derived from SMR was found to be less eco-friendly than the Li-ion. Compared with the direct GHG emissions, the FC had a greater environmental impact than that of the Li-ion battery. For the integrated GHG emissions, the FC using Bio-H$_2$ was more eco-friendly.

4. Conclusion

In this study, a drone operated using an FC battery with metal hydride storage was examined in terms of an LCA methodology. The following two results were obtained: (1) the performance, i.e., the relationship between the battery power and the thrust power, was clarified, and (2) compared with a conventional battery and an FC battery fueled by Bio-H$_2$, the eco-burden on basis of LCA was estimated.

As a result, in the manufacturing phase, the GHG emissions of the FC device would be more affected than the Li-ion device. In the use phase, the FC battery using Bio-H$_2$ achieved negative emissions because of the fuel specification.

Improvement of the performance is necessary to obtain the added value. Likewise, the eco-friendly design of drones with FC batteries is important to contribute to mitigating the global warming problem. For these problems, for instance, the expansion of flight duration and/or the reduction of total weight, including storage, would be effective.

In the manufacturing phase, it is necessary to reduce platinum as a catalyst, because it greatly affects the environmental impact. In the use phase, the suitable balance of power scale and total weight is required to expand the flight duration. For this countermeasure, the selection of metal hydride that has an adsorption capacity higher than the current level would be extremely significant. In this study, although metal hydride of 1 wt.% (= the adsorption rate of H$_2$ weight against the unit weight of metal hydride) was adopted, metal hydride with a higher capability might be effective. For instance, the metal hydride in this study can upgrade the capability to approximately 1.4 wt.% theoretically. In the future, the suitable adsorbent will be investigated.

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