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Conceptual design of small unmanned aerial vehicle with proton exchange membrane fuel cell system for long endurance mission

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ABSTRACT

Energy is the most important factor determining the performance of a small unmanned aerial vehicle (UAV) with a proton exchange membrane fuel cell (PEMFC) system because the mission capability of a small UAV is determined by the energy of its power source. For this reason, in this study, a new conceptual design process for a small UAV with a PEMFC system was investigated with respect to energy. The mission profile and requirements for the small UAV were first determined. Five reference aircrafts were selected based on mission requirements, and some input parameters were assumed for conducting analyses based on these reference aircrafts. A constraint analysis was conducted to determine wing loading and power-to-weight ratios. The wing loading and power-to-weight ratios were used for mission analysis to determine the design specifications of the small UAV. The effect of gravimetric power and energy densities of the PEMFC system on the designed UAV endurance was also investigated. Finally, performance targets of the PEMFC system were suggested for a long endurance mission of the small UAV. This study investigated a conceptual design process that can be widely used for the conceptual design of small UAVs with PEMFC systems.

1. Introduction

Small unmanned aerial vehicles (UAVs) have attracted worldwide attention owing to their usefulness. They can be used for several missions such as parcel service, disaster relief, environmental monitoring, surveillance, and reconnaissance. Various power sources have been used for small UAVs, but the existing sources have some disadvantages. Batteries limit the mission capability of small UAVs because of their low gravimetric energy density. Internal combustion engines are inefficient and noisy. Solar cells are affected by weather. Consequently, fuel cells have attracted considerable attention as power sources for small UAVs owing to their many advantages, such as high energy density, high efficiency, and low noise [1,2].

Among various types of fuel cells, direct methanol fuel cells (DMFCs) [3], solid oxide fuel cells (SOFCs) [4–7], and proton exchange membrane fuel cells (PEMFCs) have been developed for aerospace applications by research groups in countries with advanced aerospace technology. Because DMFCs directly use methanol as fuel, they are simple. However, they are unsuitable for long endurance missions of small UAVs because of their low power and energy densities. Because SOFCs are operated at high temperature, they have high efficiency. However, they are unsuitable for small UAVs because of their slow start-up time. PEMFCs have many advantages, such as high energy density and short start-up time. As a result, PEMFCs are the most suitable type of fuel cells for small UAVs.

PEMFCs use platinum as anode catalyst, but it is easily contaminated by even a small amount of carbon monoxide. Therefore, hydrogen storage systems using chemical hydride, gaseous hydrogen, and liquid hydrogen have been investigated to supply pure hydrogen to the PEMFC systems of small UAVs. The Korea Advanced Institute of Science and Technology (KAIST) [8–16] and Chosun University [8,9,17–19] developed PEMFC systems with sodium borohydride ($NaBH_4$) hydrogen generators for small UAVs. They evaluated these fuel cell systems through 1–2 h flight tests [8,9,13,17]. The Korea Aerospace Research Institute (KARI) used the Horizon Fuel Cell Technologies' Aeropak as a power source for a small UAV. The UAV flew for 5 h in October 2010 [20]. The Korea Institute of Science and Technology (KIST) investigated a PEMFC system with an ammonia borane (NH_3BH_3) hydrogen generator [21–23]. They applied the fuel cell system to a small UAV and conducted a 1 h flight test in January 2013 to evaluate it [24]. The Naval Research Laboratory (NRL) developed a PEMFC system with a gaseous hydrogen tank for a small UAV. The UAV flew for 26 h in November 2009 [25]. NRL also developed a PEMFC system with a liquid hydrogen tank. They validated the fuel cell system through a 48 h flight test in April 2013 [26].

Although many research groups have developed various types of

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Nomenclature

AR	aspect ratio
C	coefficient
D	distance (m)
e	Oswald efficiency number
ED	energy density (Wh/kg)
g	gravitational acceleration (m/s^2)
h	operating altitude (m)
k	velocity ratio
M	margin (%)
P	power (W)
q	dynamic pressure (N/m^2)
RC	rate of climb (m/s)
S	area (m^2)
t	time (min, h)
V	speed (km/h)
W	weight (kg)

Greek symbols

η	efficiency (%)
μ	coefficient of friction
π	pi
ρ	density (kg/m^3)

Subscripts

af	airframe
av	avionics
b	battery
cl	climb
cr	cruise
D	drag
em	emergency
en	endurance
f	fuel cell
h	hydrogen storage system
l	landing
L	lift
max	maximum
min	minimum
p	propulsion
s	stall
td	touchdown
to	takeoff
vmax	maximum speed
w	wing

Abbreviations

DMFC	direct methanol fuel cell
KAIST	Korea Advanced Institute of Science and Technology
KARI	Korea Aerospace Research Institute
KIST	Korea Institute of Science and Technology
NRL	Naval Research Laboratory
PEMFC	proton exchange membrane fuel cell
SOFC	solid oxide fuel cell
UAV	unmanned aerial vehicle

PEMFC systems for small UAVs using chemical hydrides, gaseous hydrogen, and liquid hydrogen, most of the research groups replaced conventional power sources of existing UAVs with the developed PEMFC systems. Because PEMFC systems are different from conventional power sources, small UAVs with PEMFC systems built for long endurance missions should be developed through a new conceptual design process. However, the conceptual design of small UAVs with PEMFC systems has not been investigated as much as those of aircrafts with other power sources such as batteries [27–29], internal combustion engines [27], and solar cells [30–34].

A conceptual design of small UAV with a PEMFC system was investigated in this study. First, a constraint analysis was conducted based on mission requirements. Wing loading and power-to-weight ratios were determined through the constraint analysis. Second, a mission analysis was investigated based on energy. Because energy determines the endurance of small UAVs, energy is an important factor for a small UAV with PEMFC system. The design specifications of a small UAV with a PEMFC system were determined through the mission analysis. Third, the effects of gravimetric power and energy densities of the PEMFC system on endurance of the designed UAV were investigated. Finally, performance targets for the PEMFC system were determined, based on the endurance of the designed UAV.

2. Conceptual design

2.1. Design process

Fig. 1 shows the conceptual design process of the small UAV with a PEMFC system in this study. First, mission requirements were proposed to develop the small UAV. Reference aircrafts were surveyed based on the mission requirements. Data from the selected reference aircrafts were used as input parameters for a constraint analysis. The constraint analysis was performed to determine wing loading and power-to-weight ratios. Mission requirements, input parameters, wing loading, and power-to-weight ratios were used for the mission analysis. The mission analysis was conducted based on energy. If the flight endurance calculated from the mission analysis is longer than the required flight

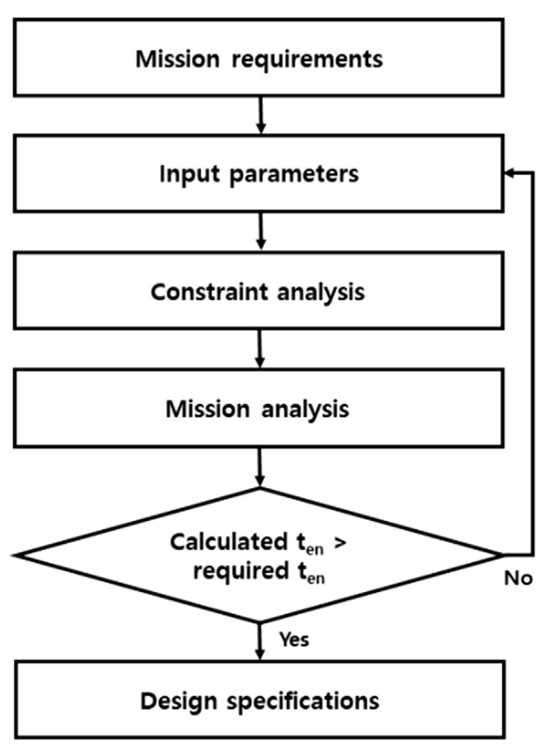

Fig. 1. Conceptual design process of small UAV with a PEMFC system.