A Fuel Cell Propulsion System
for a Mini - UAV

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**A Fuel Cell Propulsion System for a Mini UAV**

**Performing Organization:**
Royal Military Academy of Belgium

**Distribution/Availability Statement:**
Approved for public release, distribution unlimited

**Supplementary Notes:**
See also ADM001689, EOARD-CSP-03-5073 Micro Air Vehicle Workshop. The original document contains color images.
Introduction
Mission specification
Feasibility Study
Preliminary Design (with AAA)
Mini-UAV lay-out
Conclusions
Mini-UAV propulsion: various
Acoustic & IR $\rightarrow$ batteries
RMA study: a stack of fuel cells integrated in the Mini-UAV (1.5 m spanwidth)
Dragon Eye
Mini-UAV
(USA – US Navy)
2001
Our starting point: Dragon Eye (US)

Characteristics:
- Span: 1.14 m
- Speed: 18 m/s
- Endurance: 45 - 60 min
- Electric propulsion with batteries
- Propulsion system mass: 1350 g
- MTOGW: 2150 g
- Payload: ?
Our mission specification

- Payload: 1.0 kg (cam, nav, coms, PS)
- Engines: brushless DC motor with PEMFC
- Performance:
  - Max cruise speed: 16 - 18 m/s
  - Endurance: 50 - 60 minutes
  - Range: ~ 10 km
  - Direct climb to 1,000 ft
Over the hill mission

- Climb
- Loiter
- Cruise
- Descent
- Take-off
- Land

20 km
FC working principle

Main elements:
- electrodes (+ / -)
- electrolyte
- reactants
- products
Fuel Cells types

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<tbody>
<tr>
<td>Electrolyte</td>
<td>ZrO2/Y2O3</td>
<td>Li2(K2)CO3</td>
<td>H3PO4</td>
<td>membrane polymère</td>
<td>KOH</td>
<td>H2SO4</td>
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<tr>
<td>Temperature</td>
<td>800-1000°C</td>
<td>650°C</td>
<td>160-210°C</td>
<td>50-100°C</td>
<td>70-100°C</td>
<td>70°C</td>
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<tr>
<td>combustible possible</td>
<td>H2,CO</td>
<td>H2,CO,CH4,méthanol</td>
<td>H2,CO</td>
<td>H2</td>
<td>H2</td>
<td>méthanol</td>
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Ideal Selected configuration for tests

- PEMFC of 600 W

Why ? Major arguments :
- Range of powers & power density & performance
- Functionnal temperature & start-up characteristics
- Fuel used (compactness)
Feasibility Study (1)

a/c drag:
- RMA data
- FX05 profile
- Mass estimation
- Power derived
- Wing area
- Stall speed
Feasibility Study (2)

Dimensions of FC:

- D & V $\rightarrow$ required power $\sim$ 400 W
- Power for utilities (10 W camera, 22 W for 24-12V and 13 W for 24-6 V DC-DC convertors) $\rightarrow$ 50 W
- 450 W PEMFC dim & mass estimation
- Motor voltage fixes the number of cells $\rightarrow$ length (30 cells x 3 mm + side plates) $\sim$ 160 mm
- Power & Voltage $\rightarrow$ current (27 A)
- Current & density (.332 A/cm²) $\rightarrow$ $\phi_i$ $\sim$ 40 & $\phi_o$ $\sim$ 110 mm
- H2 consumption determined $\sim$ 23 g
- GH2 at 300 b $\rightarrow$ composite tank (60 x 230) $\sim$ 260 g
Feasibility study (3) : Fuel Storage

LH\textsubscript{2} or GH\textsubscript{2} → GH\textsubscript{2} MP (or other promising storage methods)

Tank size?

![Graph](image1)

\begin{align*}
\text{Tank volume} &= f(\text{pressure}) \\
&\text{for a one hour working}
\end{align*}

![Graph](image2)

\begin{align*}
\text{Tank mass evolution} &= f(\text{pressure}) \\
&\text{for different materials}
\end{align*}
Mass description:

- Mass of PEMFC: 525 g
- Mass of H2-fuel: 25 g
- Mass of full fuel tank: 260 g
- Mass of complete prop syst: 2.160 g
- Mass of payload, fuselage, wings & acc: 950 g
- Total mass: 3.1 kg
Mini-UAV

Configuration: Flying Wing + winglets
Preliminary study (1): iterations!

Mission Specification

Preliminary Sizing
- \( W_{TO} \)
- \( T_{TO} \)
- \( A \)
- \( W_F \)
- \( W_F \)
- \( C_{L,\text{max}} \)
- \( W_{PL} \)
- \( S \)

Sensitivity Studies
- Definition of R and D needs
- Refinement of Preliminary Sizing

P.D. SEQUENCE I
- Preliminary Configuration Layout and Propulsion System integration
- Configuration candidates identified and one or more selected for further study
- Sizing iteration and reconfiguration

P.D. SEQUENCE II
- Refinement of Preliminary Configuration
- Preliminary Configuration Design Finished
- Layout of wing, fuselage and empennage
- Class II: Weight, balance, drag polars, flap effects, stability and control
- Performance verification
- Preliminary structural layout
- Landing gear disposition and retraction check
- Cost calculation
Estimation of TOGW, OEW & MFW (generals of the iterative method):

- \( \text{TOGW} = \text{OEW} + \text{FW} + \text{Pay} \)
- \( \text{OEW} = \text{WE} + \text{TfoW} + \text{Crew} \)
- Correlation: \( \log \text{TOGW} = A + B \log \text{WE} \)
- If \( A \) & \( B \) known → determine mission fuel fractions (Mff) & iterate
- With also: \( \text{FW} = (1 - \text{Mff}) (1 + \text{Mf,\text{res}}) \text{TOGW} \)
- \( \text{Mff} \text{ ??? A} \& \text{B } \text{ ???} \)
Determination of Mff:

- Fuel fraction method for Mff (x of the Mffi)
- Fuel unintensive segments (statistical data)
- Fuel intensive segments (Breguet eq. for R & E)
- FC $\rightarrow$ Breguet eq N/A $\rightarrow$ hand calculation
- $Mff = 0.9919$
Determination of A & B:

- Correlation: \( \log \text{TOGW} = A + B \log \text{WE} \)
- Problem: statistics N/A to UAV (mini !!)
- Own data base with electrical UAV & mini
- Small error for our PEMFC but PD 1
- \( A = 0.1937 \) & \( B = 1.0094 \)
Results:

- \( \text{TOGW} = 3.97 \text{ kg} \)
- \( \text{WE} = 2.92 \text{ kg} \)
- \( \text{FW} = 32 \text{ g} \)
- Compared with 3.1 kg, 2.1 kg and 23 g
Estimation of the drag polar:

- \( CD = C_{do} + \Delta C_{do} + CL^2/(AR e \pi) \)
- \( C_{do} = f / Sw \) (parasite area (f) method)
- Rationals: \( \log Sw_{et} = c + d \log TOGW \) or \( \log f = a + b \log Sw_{et} \) (a, b, c & d based on Cf)
- AGAIN PROBLEM (due to FW configuration)
- Other method: for FW, \( Sw_{et}/Sw \sim 2.1 \) (with SM)
- FW data: \( AR = 5 \) & \( e = 0.85 \)
- Try various \( Sw \rightarrow Sw = 0.45 \text{ m}^2 \rightarrow CD \)
- \( CD = 0.0125 + 0 + 0.0749 CL^2 \)
Preliminary Design (7)
Performance sizing:
- Restrictions on W/S at TO & W/P at TO
- Catapult launch & ventral or “net” ldg
- Vs in cruise & MTOGW : 12.1 m/s
- Climb : grad (Mil Specs) & Tclb of 2’
- Max cruise speed at MTOGW
- Maneuvering distance : nmax = 2.0 at MTOGW
Preliminary Design (9)

DESIGN POINT
Performance sizing:

- Try different Sw in order to increase performance and minimize engine
- Final results: \((W/S)_{TO} = 86 \text{ N/m}^2\) & \((W/P)_{TO} = 120 \text{ N/kW}\)
- Power of the PEMFC = 325 W + 50 for acc
- We had selected one of 450 W \(\rightarrow\) SF = 1.2
Selection of the wing (1)

Wing profile:
- Need of a fuselage (integrated in the planform)
- $C_{l,\text{max}}$ in accordance with sizing requirements
- $C_{l,\text{max}} \sim 1$
- High taper ratio in order to decrease trim drag but "neglectible" here
- $\frac{1}{4}$ chord sweep (stability with 2-cambered profile)
- Eppler 325, $AR = 0.6$, $\Lambda = 30^\circ$ ($C_{l,\text{max}} = 0.96$)
Selection of the wing (2)

- $c_{l,w} = 0.38\ m$
- $x_{mgc_w} = 0.22\ m$
- $c_{w} = 0.31\ m$
- $y_{mgc_w} = 0.34\ m$
- $b_w/2 = 0.75\ m$
- $c_{t,w} = 0.23\ m$
Mini-UAV

Configuration: flying wing with winglets
Internal Elements: energy distribution
Internal architecture

- Brushless motor + command
- Hydrogen tank
- Back-up battery
- PEM Fuel Cell
- Communication system
- DC-DC converter
- Regulation gate
- Payloads
PEMFC stack by Novars GmbH

- PEMFC of 600W
- $V_c = 0.6V$, $V_{tot} = 24V$ (40 cells)
- mass = 780g
- $\varnothing = 110mm$
- $L = 200mm$

Special architecture

Complete system:
- 220 Wh/kg energy density
- 2.27 kg mass system
Longitudinal Stability

StM :
- 4.8 cm
- 16.4 %
## Comparison with the Dragon Eye

<table>
<thead>
<tr>
<th></th>
<th>Dragon Eye</th>
<th>MAV PAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wingspan [m]</td>
<td>1.14</td>
<td>1.5</td>
</tr>
<tr>
<td>Speed [m/s]</td>
<td>18</td>
<td>18 max</td>
</tr>
<tr>
<td>Range [min]</td>
<td>60</td>
<td>60</td>
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</table>

### Masses [g]

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<tr>
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<tr>
<td>Propulsion System</td>
<td>1350</td>
<td>2620</td>
</tr>
<tr>
<td>Complete Aircraft</td>
<td>2150</td>
<td>3950</td>
</tr>
</tbody>
</table>

| Power [W]        | 300        | 450      |
The test bed at RMA

Schematic

- DC-DC converter
- Telecom. card
- Control station
- Portable radio station
- Antenna
- Gear box
- Brushless motor
- Flexibles pressure distributor
- Pressure reducing stage 1: VHP-MP
- Pressure reducing stage 2: MP-Atm
- VHP Hydrogen tank
- Forcled flow PEM Fuel Cells
- MEA (membrane electrode assembly)
- Interconnexion (bipolare) plate
- Plexyglass enclosure
- Cooling fan
- Thermometer T1
- Hygrometer
- Torquemeter
- Photo-electric tachymeter
- Pressure gauges P1, P2, P3
- Pressure reducing stage 1: VHP-MP
- Pressure reducing stage 2: MP-Atm
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-Thrust measurement system
Our Fuel Cell

**Technical datas**

- PEMFC stack of 500 We
- 32 cells and $V_c = 0.625V$ so $V_{tot} = 20\, V$
- A current of 25A is available
- The mass is about 6kg (power density 3 x lower)

**Cooling system:**
- $<200\, We$ forced air by 4 fans
- $>200\, We$ forced air+distilled water system
Conclusions (1)

- 1st : Basic calculations in order to check the feasibility
- Compatible PEMFC are available ($ !!)
- 2nd : More detailed calculations (AAA)
- Planform determined & stability possible
- Test Bench : Acquire knowledge about small PEMFC in practice
Conclusions (2)

- Improve current systems (fueling, storage, etc.) & control the required mass & volume of the whole propulsion system
- Miniaturise the complete propulsion system in a future exercise
- Increase the power density of complete FC propulsion system
- Future: other FC options
- Thanks to a few students from Fr & NL
Questions ?