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Hybrid Fuel Cell – Battery System as a Main Power Unit for Small Unmanned Aerial Vehicles (UAV)

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This paper describes designing procedure of an unmanned aerial vehicle (UAV) supplied with a commercial AEROPACK hybrid system consisting of a fuel cell stack and a battery pack. During preliminary tests, the following characteristics of the hybrid system were investigated: voltage-current dependences, stability of performance for various loading and H_2 sourcing (pressurized cylinders or chemical source of H_2), interaction between fuel stack and battery pack in supply of propulsion system and consumption of hydrogen fuel as a function of loading. It was shown that during a continuous current loading up to 5.5-6.0 A, the current withdrawn from the AEROPACK system comes almost exclusively from the fuel cell stack, only at higher loadings it is complemented from the battery pack. These tests enabled us to determine the thermal efficiency of the fuel cell stack and estimate the expected time of flight with different H_2 sources, covered without the need to refuel. A small, high-pressure composite cylinder appeared to be useful only for short test flights of UAVs, whereas longer missions require using a cartridge with chemical fuel. The preliminary tests of the propulsion system (a propeller-motor-hybrid power unit) were done in the laboratory ground facilities. Unfortunately, the first tested type of motor (Hacker C50 13XL brushless) appeared to be too large and powerful for the UAV prototype. A search for a more appropriate electric motor with lower power and smaller dimensions and further adoption of the propulsion system are described in the paper. Finally, successful test flights of the UAV prototype equipped with AEROPACK hybrid system are presented.

Keywords: unmanned aerial vehicle, electrical power source, fuel cell, flight, polymer membrane fuel cell stack, Aeropack

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) are mainly used for surveying and surveillance. These applications have very specific constraints on power, cost, weight, space and flight endurance. The most important element of UAV equipment affecting the mission performance is power source, which should have high power and energy densities, and operate with high efficiency. The power density has a decisive influence on maximum speed, load capacity, altitude of flight and rate of climbing whereas energy density impacts time (range) of flight covered without the need to refuel or recharge the energy accumulator [1-3].

The term "power density" in this paper is defined as the ratio of power to the total weight of a unit with a drive unit, fuel tank, and an energy accumulator, as well as any auxiliary devices. The power density of a system is determined usually by the weight of the fuel tank or energy accumulator (battery pack, swing-wheel, pressure vessel).

Most of the state-of-the-art UAVs are powered now with internal combustion engines due to their considerably higher power and energy densities in comparison to electrical drive units (usually, by approximately an order of magnitude) [4-6]. Electrical motors today are considered only as a limited drive unit even for cars, boats, as well as planes of all types, despite their undoubted merits, such as efficiency and quiet operation, beneficial power and torque characteristics in the field of frequency of rotation, pro-ecological character (no combustion exhaust gases), relatively low costs of investment, high reliability, etc.

2. POWER SOURCE FOR UAVS: FUEL CELLS VS. ELECTROCHEMICAL BATTERIES AND COMBUSTION ENGINES

Despite these impairments, silent UAVs powered with an electric motor are now intensively developed since low acoustic and heat emissions are also required to hinder detection and facilitate performing the mission [7,8]. Fuel cells (FC) as power source for electric propulsion of UAVs show growing applications because of their energy densities that exceed 800Wh/kg in comparison to 150Wh/kg for advanced batteries. Hence, FC system weights are ca. 3.5 times less than a Li-ion battery with similar parameters, and 8 times less than a nickel metal hydride battery, and even 16 times less than a lead-acid battery pack [9,10]

The additional advantages of FCs over advanced batteries are: reduced size, lower life cycle cost and extended run times. A long-lasting effort in both research and development led to the commercial emergence of electric power generators based on the fuel cell systems. The recent technological developments in the field of fuel cells, especially in materials engineering, resulted in decreasing mass per unit area (hence, in increasing power and energy densities). This has allowed practical applications of FCs in aviation.

A fuel cell differs from other galvanic cells by way of its “charging” - active electro-chemical substances, i.e. these which take part in electrode processes, are supplied externally and the products of the reaction are discharged outside of the interior of the FC. The FC operates as long as there is fuel (usually hydrogen) and an oxidizing agent (usually oxygen taken from air) [11,12]. The principle supply of a fuel cell is the same as an internal combustion engine (which also needs an externally supplied fuel and oxidizing agent, and discharges combustion exhaust gas). However, the energy conversion process is done in a single step (direct conversion) and leads to producing electric energy, while in an internal combustion engine it consists of two steps (chemical energy of fuel → heat → mechanical energy), and leads to producing mechanical energy. In both cases, due to an irreversibility of the processes in the devices, exhaust heat is created. FCs, practically, do not emit exhaust fumes except small amounts of water vapour, which means no emission of smell or smoke. Heat emission is also considerably small which makes planes practically untraceable by means of infrared devices for tracking and destroying targets (especially with night-vision modules). Lack of moving parts decreases vibration, as well as simplifies service and increases reliability. In contrast, internal combustion engines are noisy, have low thermal efficiency and high heat emission [13-14].

3. TYPES OF FUEL CELLS AND THEIR USEFULNESS FOR UAVS

Fuel cells are generally classified into two basic categories, regarding types of electrolyte used and operation temperatures. In the former category, five main types of fuel cells are distinguished [15 - 18]:

- Electrolyte Membrane Fuel Cell or Proton Exchange Membrane Fuel Cell – PEMFC,
- Alkaline Fuel Cell – AFC,
- Phosphoric Acid Fuel Cell – PAFC,
- Molten Carbonate Fuel Cell – MCFC,
- Solid Oxide Fuel Cell – SOFC.

The basic parameters and plausible applications of different types of fuel cells are summarized in Table 1.

Table 1. The basic parameters and plausible applications of different types of fuel cells

	DMFC	PEMFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Polymeric H^+ ion exchange membrane	Polymeric H^+ ion exchange membrane	alkaline salt, water solution or molten mobile or matrix electrolyte	liquid phosphoric acid matrix electrolyte	liquid molten carbonate matrix electrolyte	ceramic
Operating temperature	20-90°C	30-100°C	50-200°C	~220 °C	~650 °C	500-1000 °C
Power range	1-100 W	1-500 kW	500 W-10 kW	10 kW-1 MW	50 kW - 10 MW	1kW-10MW
Applications						

Portable electronics	Military applications, emerging civil market, UPS					
Cars, boats, and spaceships		Propulsion (cars, boasts), power source (spaceships)	Power source (spaceships), special applications			UAVs, auxiliary power unites
Domestic CHP		Fueled with natural gas reformed externally to H_2				Fueled with natural gas reformed externally or internally to H_2
Distributed power generation, CHP, propulsion		Busses, submarines, stationary CHP generators		Stationary CHP generators, large ship (MCFC),		

	DMFC	PEMFC	AFC	PAFC	MCFC	SOFC
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Distributed power generation, CHP, propulsion		Busses, submarines, stationary CHP generators		Stationary CHP generators, large ship (MCFC),		

At the present state of technology, the PEMFC shows a relatively high level of development – a variety of different systems with these cells are already available in the marketplace. Moreover, the PEMFC operates in a temperature range of below 100^{o}C, which is suitable for its application as an electricity source in UAVs. Therefore, a majority of the demonstration aircrafts have used PEM fuel cell generators to supply their drive units [19].

Usually, the PEMFCs in UAVs are fed with hydrogen fuel, which must be either stored or produced onboard. A variety of hydrogen storage systems have been used, including gaseous pressure vessels, chemical hydrates and low pressure cryogenic liquid hydrogen tanks. On the contrary to the direct hydrogen storage, production of H_2 from methanol or other hydrocarbons (kerosene, gasoline or diesel) needs additional onboard equipment (steam reformers, partial combustion or auto thermal reactors and control systems) but takes advantage of the compact storage tank of liquid fuel [20]. Unfortunately, the hydrogen content in gaseous fuel produced by the reforming process is significantly lower than 100% (e.g. product of methanol steam reforming contents 75% of H_2), which reduces the efficiency of the FC and its peak power output.

To utilize methanol fuel for powering UAVs, a direct methanol fuel cell (DCFC) can be used hypothetically instead of a system consisting of a PEMFC and an onboard reformer. A DCFC is similar to a PEMFC in that the electrolyte is a polymer and the charge carrier is a hydrogen ion. The liquid methanol (CH_3OH) is oxidized directly in the cell, producing electricity [21]. However, the overall efficiency of a DCFC is considerably lower than that of a PEMFC, even when much larger quantities of expensive catalyst (generally platinum) are used at the electrodes to accelerate the rate of electrode processes. In addition, the anode has a limited carbon monoxide tolerance, which is also formed in minor amounts during methanol oxidation. Therefore, the DCFC has not been applied as yet in the already tested UAVs. Other disadvantages of widespread use of methanol are its high toxicity and the fact that generally CH_3OH cannot be classified as a biofuel. Such restrictions do not concern ethanol, hence investigations in both applications: direct ethanol fuel cells and reforming of C_2H_5OH are now under way in many institutions [22].

The operating range of high-temperature state-of-the-art SOFCs is currently around or above 800^{o}C. Recent developments are aimed at entering the range around 700^{o}C. Therefore, CO in the fuel represents no problem for SOFCs due to the high temperature of operation, which eliminates the need for using platinum catalysts, sensitive to presence of carbon monoxide. Moreover, at the conditions of SOFC operation, most of the hydrocarbons, including basic aircraft fuel - kerosene, can be reformed internally in the cell. This opens a new perspective for employing onboard reforming processes to supply the fuel cells in aircrafts, although first of all regards onboard auxiliary power units and propulsion of large planes [23].

One of rare cases of using the SOFC in UAVs is the propane-butane fuelled unit constructed in 2006 by Advanced Materials Inc. AMI, until now, has focused most of its efforts on military applications of its SOFCs, such as individual power sources for soldiers and propulsion systems for unmanned vehicles. The company has developed 50- and 250-watt SOFC stacks that can be fuelled with off-the-shelf propane-butane canisters [24,25].

4. REPRESENTATIVE PROTOTYPES OF UAVS WITH FUEL CELL STACKS

Several fuel cell powered aircrafts have been recently built as final yields of many research projects contracted between scientific institutions and industrial companies involved in UAVs and fuel cells in the USA, Europe and Asia. Selected representative prototypes of UAVs with fuel cell stacks are described below:

(a) HALE, constructed in 2005 by Aero Vironment, a high-altitude long-endurance UAV, was the first aircraft fuelled with liquid hydrogen. Then, the company made use of the acquired experience for construction of the larger Global Observer, also fuelled with liquid hydrogen (powered by eight propellers located on the leading edge of a 15 m wingspan) [26];

(b) Mako, produced by Jadoo Power, which used commercially available PEM fuel cell stack and packing components. The prototype was flight-tested by the Office of Navy Research (ONR) at the US Army Yuma Proving Ground in Arizona. The Mako flew for more than an hour, consuming only 8 g of compressed hydrogen in its 63 W fuel cell generator [27];

(c) Puma, a product of the US Air Force Research Laboratory (AFRL), powered with a highly advanced Protonex ProCore™ fuel cell system from Protonex Technology. This UAV aircraft is able to fly continuously for more than 7 h [28];

(d) Ion Tiger, produced by the US Naval Research Laboratory, weighs approximately 17 kg and carries a 1.8–2.3 kg payload. The 550 W (0.75 hp) fuel cell stack onboard the Ion Tiger has about four times the efficiency of a comparable internal combustion engine that provides over 26 h flight duration [29];

(e) Boomerang, product of Blue Bird company, a field-operational, 9 kg electric UAV, which is now able to fly for more than 9 h using Horizon's high-performance hydrogen fuel cell power system [30].

More examples of UAV powered with fuel cells and their descriptions can be found in the following papers [19 -30].

5. PEMFCS IN UAVS – CHARACTERISTICS OF OPERATION

Open circuit voltage (OCV) of an unloaded oxygen-hydrogen PEM fuel cell operating in the standard conditions only slightly exceeds 1 V (the electromotive force of the reversible fuel cell EMF = 1.023 V). When the loading of the FC increases, the voltage drops due to the growing effects of irreversible processes in the cell. Low voltage and power provided by a single fuel cell is useless for most drive units – thus fuel cells need to be connected in stacks, which results in increasing the power by (1) increasing the voltage in serious connection of FCs and (2) decreasing internal resistance in parallel connection of FCs. Usually, a fuel cell stack is built as a compact gas-electric system which, apart from membrane-electrolyte assemblies (MEA) and the so called diffusion electrodes, also consists of electric current collectors (bipolar plates) used as a coupling between the individual fuel cells. Besides acting as an electric connection, bipolar plates provide the spreading of the fuel and oxidant over the entire surface of each diffusion electrode [31,32].

Commercially available fuel cell stacks with a power of over 100 W require cooling, which can be realized by a stream of gaseous or liquid agent. An electric power generator based on a PEMFC stack is equipped with many auxiliary devices, which enable the control of its operation, such as: monitoring systems for moisturizing and dosing gases, cooling and temperature control systems, hydrogen leakage sensors and start-up devices [33-35].

Water cooling systems show good cooling capabilities but they are rather not appropriate for UAV applications since subsystems such as coolants, coolant tanks and pumps are complex, bulky and heavy. Generally, in these applications, an air-cooling system is recommended, because it consists of simple components and is relatively light. Air flows through the intakes and cools the stack and other systems down. The heated air is emitted through the exits and can be forced by either a system of fans or the exhaust of propellers.

An UAV consumes relatively large volumes of hydrogen fuel during its mission (a couple of normal cubic meters). Although the weight of this fuel does not create any problems due to the low specific gravity of H_2, its storage onboard can be troublesome because of room restrictions. The PEMFC stacks can be supplied by various types of hydrogen fuel tanks, however, the most popular is a composite, high-pressure (up to 700 bar) tank of H_2 or a chemical source of hydrogen (gaseous hydrogen is released in the reaction of hydride with an ion bond e.g. sodium borohydride with water) [36,37]

6. DESIGN AND TESTS OF A UAV WITH AN AEROPACK – FUEL CELL SYSTEM

This paper describes the procedure of designing an unmanned aerial vehicle (UAV), which employs a commercially available fuel cell system. The special emphasis was put on electrochemical performance of the power unit under different conditions of operation. Because the power unit consists of a fuel cell stack and a pack of Li-ion batteries, the interaction between these two sources of power during operation of the propulsion system was also carefully examined. The research embraced not only these electrochemical sources of power but also the selection and adoption of electric motor and propeller type.

6.1. Conceptual design of UAV

The airframe was designed in a high-wing (shoulderwing) monoplane system with a horizontal top tailplane. Due to the limited power and relatively high weight of the fuel cell system, the emphasis was put on low load of surface and high load capacity during the design of the UAV. The aircraft was designed as a glider, whose take-off was supported with a winch, cruising due to a drive enabling flight without falling at a low power rating of about 200 W. Airframe span was 3,000 mm, length amounting to 2,300 mm, lifting (supporting) surface was 105 dm^2, the estimated take–off weight was about 5,500 g and the load of surface was approximately 52 g/dm^2. For the design of the wing a Wortmann FX-60-126 profile was used, while the NACA 0009 profilewas used for the tailplane. The prototype UAV made for the initial tests is presented in Fig.1.

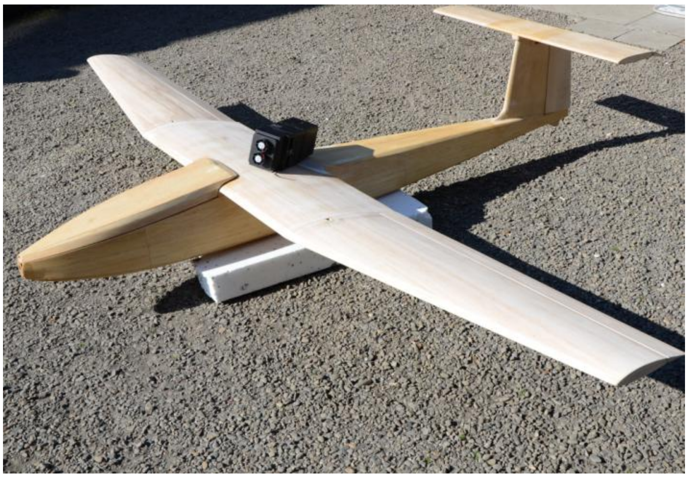


Figure 1. UAV prototype made for preliminary tests.

6.2. Selection of 250 W fuel cell stacks for powering an ultra-light reconnaissance aircraft

The preliminary phase of the project was dedicated to the estimation of the most important parameters of fuel cell stacks, which would be used as the unit powering the electric motor of the designed plane. These parameters derive from the conditions presented in Section 6.1., and were the basis for surveying the commercial market of fuel cell stacks. Possible modification of the unit was also considered due to better adoption to the aircraft requirements. Unfortunately, not all the fuel cell stacks, described in the professional literature, were available on the commercial market, when the analysis was performed. Among these which could be purchased, the most suitable power unit for the project was an AEROPACK fuel cell stack produced by Horizon, a company from Singapore. The photograph of the AEROPACK power unit is presented in Fig. 2. Table 2 presents the main results of the market survey [38-42].

Table 2. Overview of commercially available fuel cell systems for unmanned aerial vehicles. The data are in accordance to these published in references [38-41].

Trade name	PRODUCER OF FUEL CELL STACKS FOR UNMANNED AERIAL VEHICLES				
	Horizon Fuel Cell Technologies, Singapore		Protonex, Technology Corporation, USA	Energy Or. Technologies, Canada	Jadoo Power Systems Inc., USA
System	AEROPACK	H-300W (*)	UAV C-250	EPOD EO-210 LE	TIGERSHARK
Voltage range, [V]	20-30 V	70-43	----------	30-45	13,2
Nominal electric power, [W]	200	300	250	250	150
Maximum instantaneous electric power, [W]	600	-------	-------	850	225
Fuel tank	compressed hydrogen or chemical source of hydrogen	compressed hydrogen	chemical source of hydrogen	chemical source of hydrogen	chemical source of hydrogen
Weight (system + fuel) [kg]	1.7 (unit weight with chemical source of hydrogen)	2.45 (without the fuel tank)	1.2 (without the fuel tank)	2.95	10

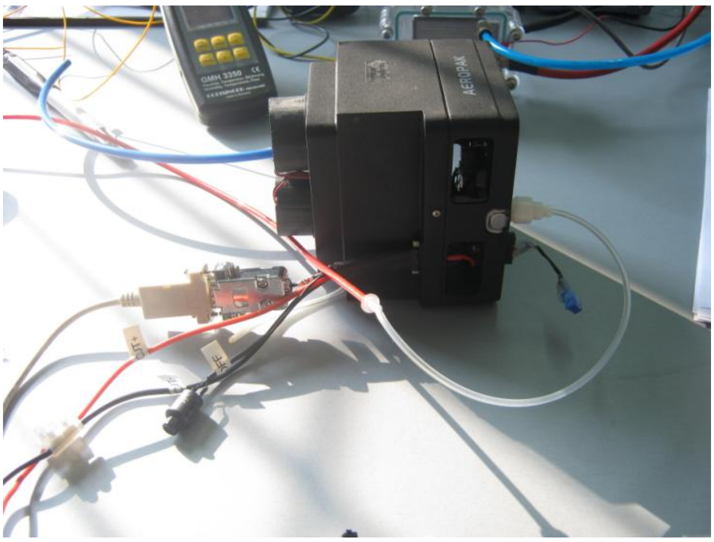


Figure 2. Commercial AEROPACK hybrid system (fuel cells and auxiliary battery pack) produced by Horizon (Singapore).

The AEROPACK is one of many commercially available fuel cell systems from Horizon that can be customized to fit a variety of platforms, and scaled up to provide as much as several kWs of power, making it suitable for all sizes and configurations of electric powered UAVs [42]. The Horizon Fuel Cell Technologies also offer a wide range of standard "off-the-shelf" PEM fuel cell systems - from 10 W to 5 kW. The PEM stacks made by this company were previously applied as power units in pioneering flights, which include “Hyfish”, a 1 kW fuel cell powered jetwing UAV integrated by the DRL German Aerospace Center [43], the “Pterosar”, which set a world distance record in late 2007 with NASA support [44].

6.3. Operational characteristics of AEROPACK PEMFC stack

Each galvanic cell (including a single fuel cell as well) and a fuel cell stack is characterized by the maximum power represented by a pair of $(\text{voltage-current})_{max}$ parameters.. For some types of galvanic cells, this point may not be observed at the power-current dependence, when its position is way out of the range of useful voltages or currents. In the case of fuel cells, the position of $(\text{voltage-current})_{max}$ point is usually clearly marked and plays an important role in the performance of the generator. Gradual loading of fuel cell stack leads to a self-regulating change in the work conditions (voltage drop, current increase, enhancement in the amount of hydrogen fuel used), which leads to an adequate increase in the power drawn from the stack, according to rising need. This action will be efficient until the maximum power point is achieved – after that a rapid fall in power supplied by the cell stack is observed despite the increasing load current. The created shortage in the power balance of the drive unit may lead to a loss of aerodynamic lift with dramatic consequences for the plane.

In the case of instantaneous power deficit, a frequently used solution is the employment of an auxiliary unit consisting of a storage battery pack or super-capacitor system. The AEROPACK unit is preset with a Li-ion battery pack - it is extremely important to determine the voltage-current and power-current characteristics of the complete system to be sure that the above-mentioned deficit of power does not occur even in unusual conditions of aircraft operation.

To test the FC stack assigned to the UAV, specially designed test facilities enabling the determination of the FC characteristics were constructed. These facilities consisted of the following instruments and auxiliary devices:

1) a XBL-50-150-800AIR programmable electronic load (Dynaload, USA) and work monitoring system for fuel cells and stacks (Fuel Cell Monitor, Gamry, USA);

2) an installation for distribution of technical gases (argon, oxygen, air and hydrogen) with an option of introducing other technical gases and their mixtures to the system. Flow-rates of supplied gas streams were controlled;

3) a manifold, which made it possible to supply fuel to a FC stack from different sources, such as composite high-pressure tanks, storage tanks with metal hydrides and chemical hydrogen sources;

4) clampmeters for electric measurements, which enabled us to determine the total current derived from the hybrid system and the partial currents derived from the PEM stack and battery pack simultaneously;

5) a miniature auxiliary device for controlling speed and humidity of gases, tested as potential elements of UAV's equipment;

6) a hydrogen detector with an alarm system (mandatory according to industrial health and safety, as well as fire safety requirements).

Firstly, the AEROPACK system was supplied with hydrogen from a standard steel cylinder.

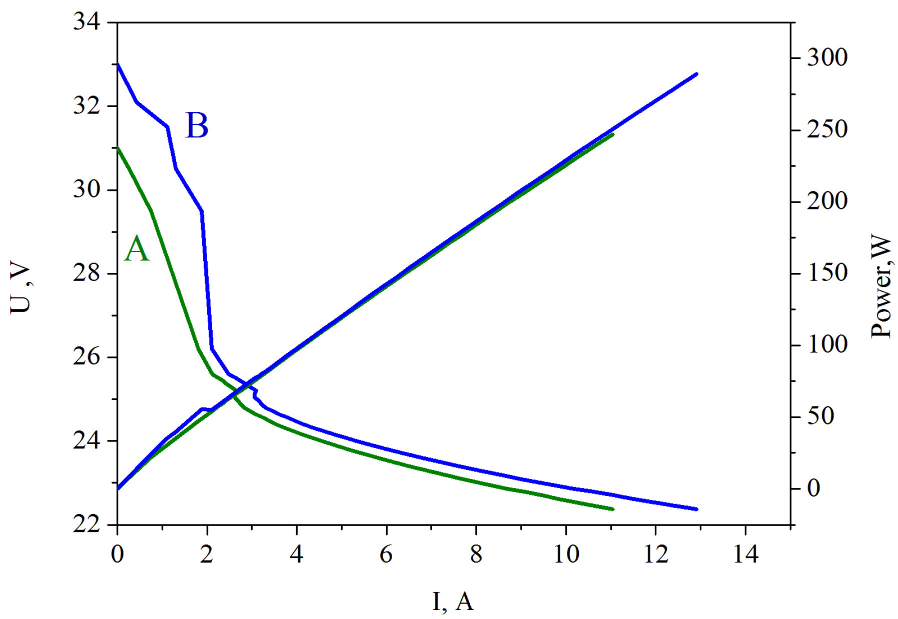


Figure 3. a) The voltage (*U*) – current (I) and power (P) – current (I) dependences determined for the AEROPACK hybrid system. The fuel cell stack was supplied with compressed hydrogen from the regular steel (A) and composite cylinder (B).

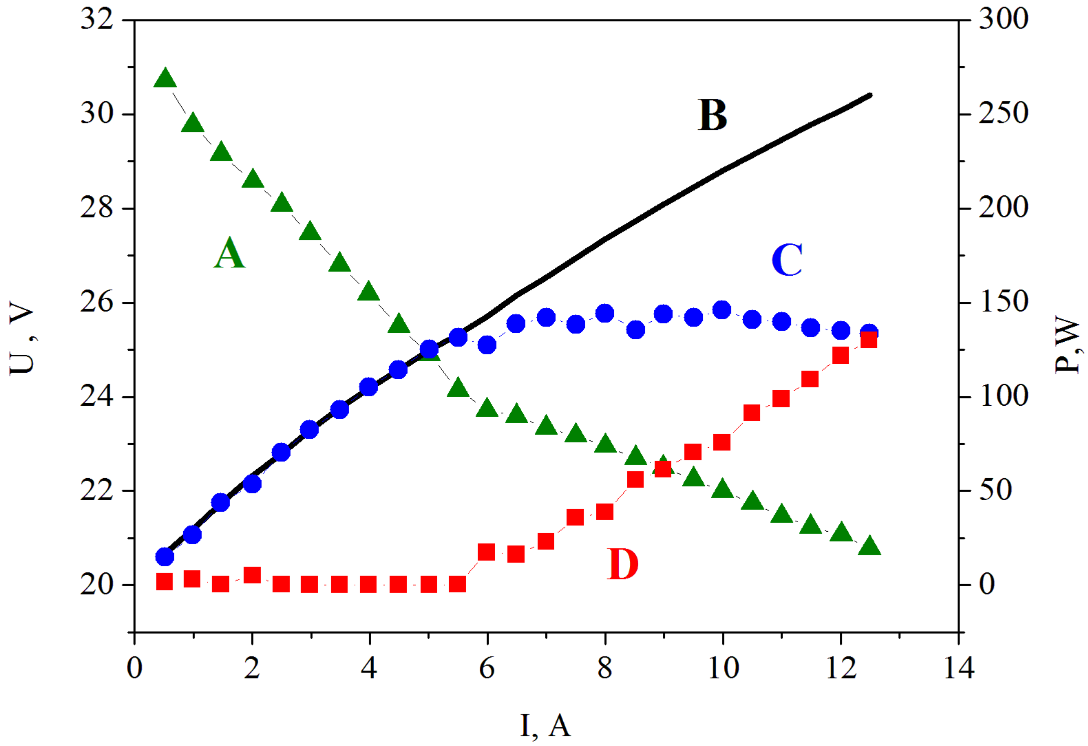


Figure 3. b) The voltage (*U*) vs. current (*I*) (A) and power (*P*) – current (*I*) (B) dependences determined for Areopack hybrid system (battery + PEM stack) . Tthe separate curves P-I for the battery pack (D) , and PEM stack (C) only were added

Then a composite carbon-fibre reinforced high–pressure container of volume 1.1 l, provided by the producer, was used. In both cases, the overpressure of H_2 supplied to the FC stack was reduced down to 0.4 bar. After examining the operation of the AEROPACK system under the conditions of external supply with gaseous H_2, the furthest part of the test, with the chemical source of hydrogen, was made. This chemical source of hydrogen is an integrated part of the AEROPACK system, designed especially to reduce the weight of the propulsion unit in UAV aircrafts. H_2 is formed as a product of reaction between light chemical hydrates and water, providing 900 Wh of net usable energy from a type I fuel cartridge containing 1 l of chemical fuel [38].

The voltage *(U)* –current *(I)* and power *(P)* – current (I) dependences, determined in the above described experiments is shown in Fig. 3 a. The presented relations allowed us to estimate the parameters of maximum power point of the tested PEMFC stack at: $(30\text{-}35\ \text{A},\ 12\text{-}14\ \text{V})_{max}$. The position of this point was outside of the current range recommended by the producer, hence its direct determination was impossible.

The combined effect of supporting the fuel cell stack from the Li-Po (lithium–polymer) battery during high power demand is shown in Fig.3b. Up to 5.5-6.0 A, the current withdrawn from the AEROPACK system comes almost exclusively from the fuel cell stack, only at higher loadings it is complemented from the battery pack. In these circumstances, there is no threat that the power demand will exceed the point of maximum power at the characteristic of FC stack due to the limited power of the electric motor, the position of maximum power point of the FC stack (outside of the available range of current) and the counteraction of the hybrid system with the battery pack.

With the determination of the electrical characteristics of the system, the measurements of hydrogen consumption were also performed simultaneously using a Bronkhorst mass flow-meter (EL-Flow F-201CV-2K0-RAD-00-V). The dependence of the stream of hydrogen consumed by the electric power produced by the fuel cell stack is presented in Fig.4.

A slight deviation from the linear character of the plot indicates that the Faradaic efficiency of the FC stack varies slightly with the loading. The thermal efficiency of the PEM fuel cell stack in electricity generation can be estimated from the equation:

$$\eta_{th} = \frac{P}{\dot{m} Q_h} = \frac{a}{\rho Q_h} \quad (1)$$

where, P is the power of FC stack, $\dot{m}$ is the mass stream of H_2, Q_h = 141.88 MJ/kg is the higher heating value of H_2, a = 0.0932 J/ml is the slope of dependency presented in Fig.4 and ρ = 0.084 kg/m^3 is the density of H_2 at 1 bar and 20°C. The thermal efficiency of examined units appeared to be satisfactorily high $\eta_{th} \approx 0.469$.

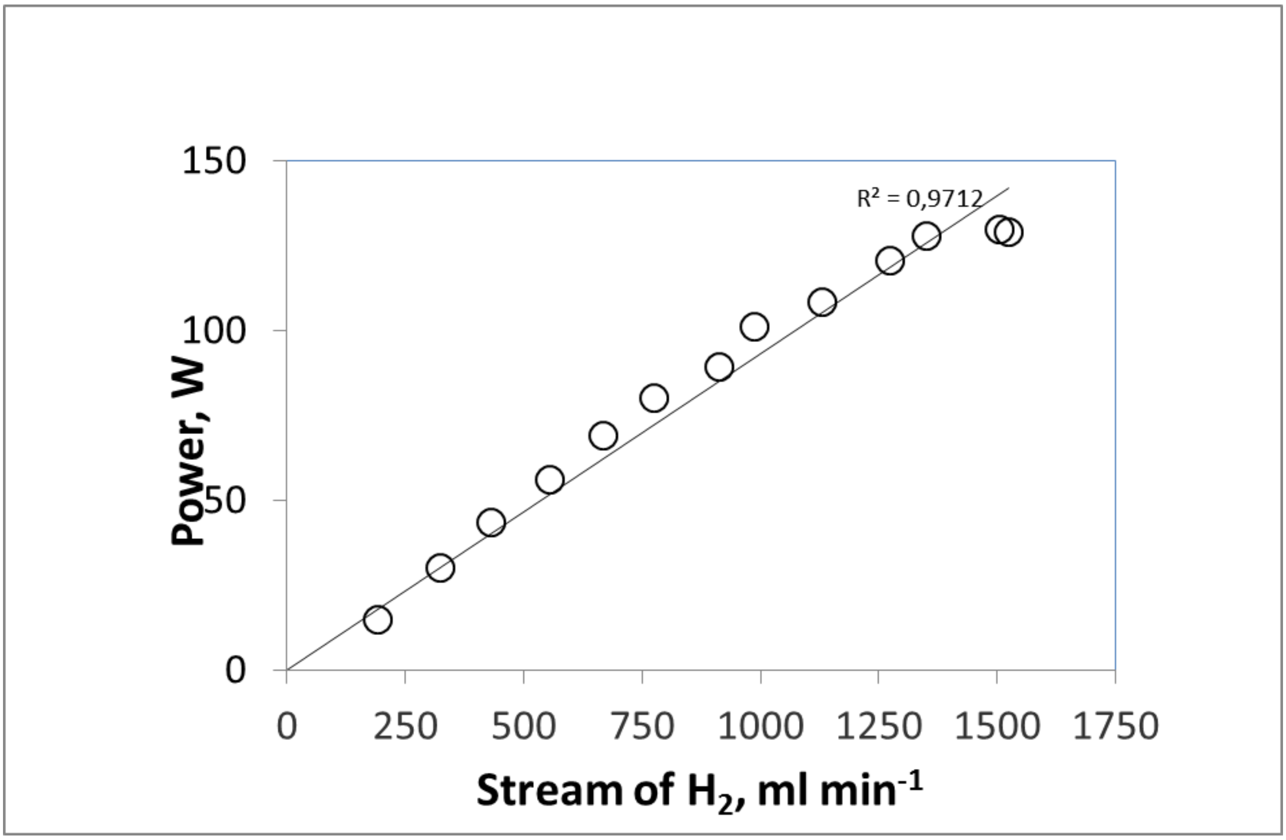


Figure 4. The dependence of the stream of hydrogen on the electric power produced by the AEROPACK fuel cell stack.

Dependable operation of the propulsion system in an aircraft relies not only on proper co-operation of its components but also on the stable and reliable operation of these components for the whole duration of the flight. The stability tests of the AEROPACK system was performed for a duration of 2 h, i.e. time of planned flight tests. The results of these experiments are presented in Fig.5a-c.

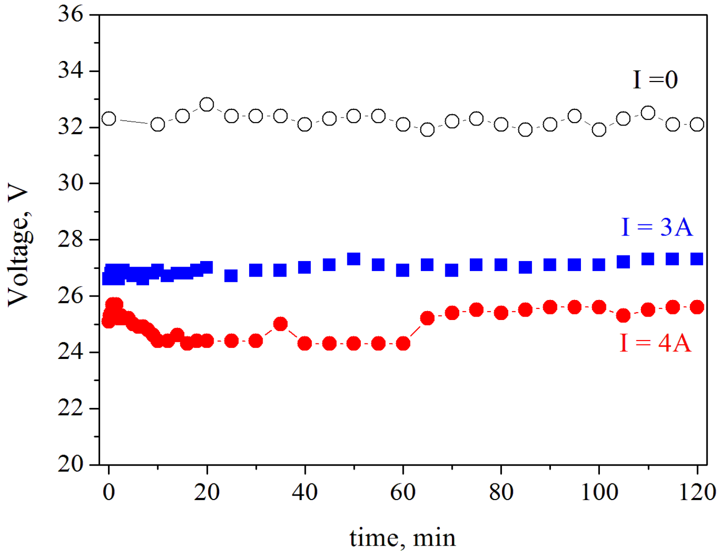


Figure 5. a) Time stability of voltage at the output unloaded (OCV, I=0) and loaded with the constant current (I_1 = 3 A and I_2 = 4 A) hybrid system;

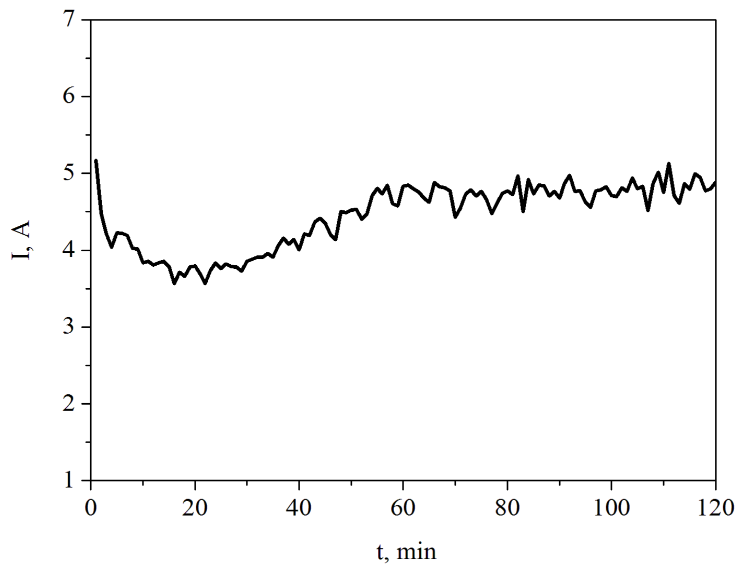


Figure 5. b) dependence of the current (I) on the time during loading with the constant voltage U = 24 V

Firstly, the voltage stability of the hybrid system, unloaded (OCV) and loaded with the constant current (I_1 = 3 A and I_2 = 4 A), was examined (Fig.5a), then the system was loaded with the constant voltage ΔV = 24 V (Fig.5b).

The OCV reached a stable value after 30 s, which was held for the whole duration of the experiment. A similar behaviour was observed in the case of loading with I_1 ,I_2, and I_3, although the voltage of the unit decreased due to appearance of activation, ohmic and concentration polarizations in the PEM fuel cells (in these conditions, the Li-Po battery pack did not participate in the electricity production).

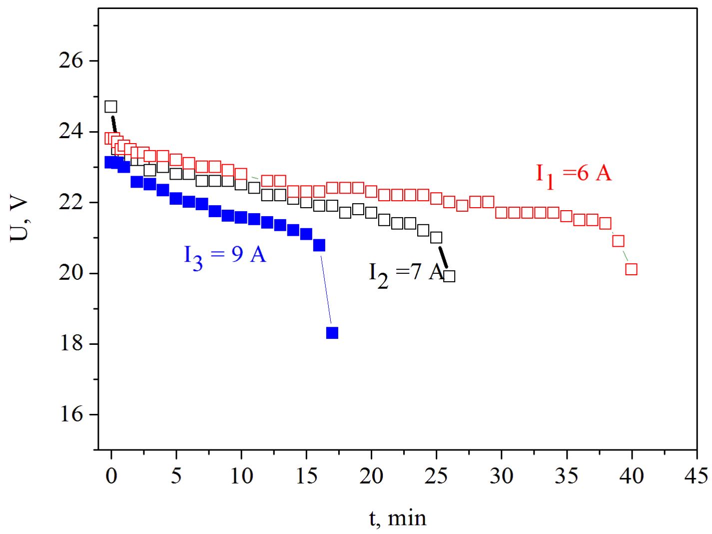
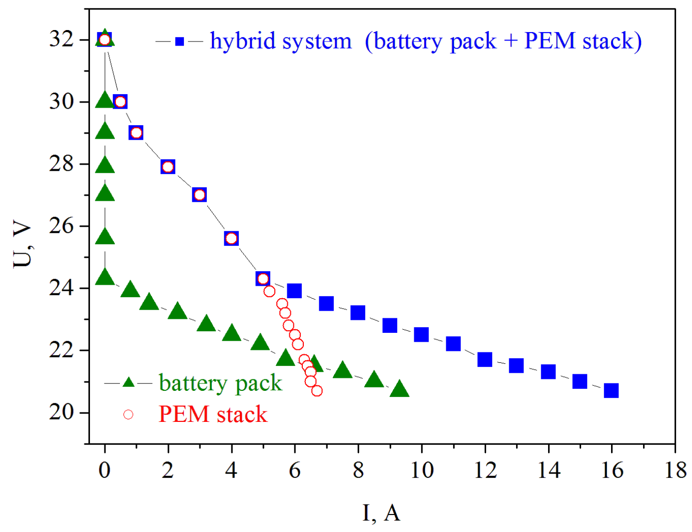


Figure 5. c) dependence of the voltage (*U*) on the time during loading with the constant current I_1 = 6A, I_2 = 7 A, I_3=9A

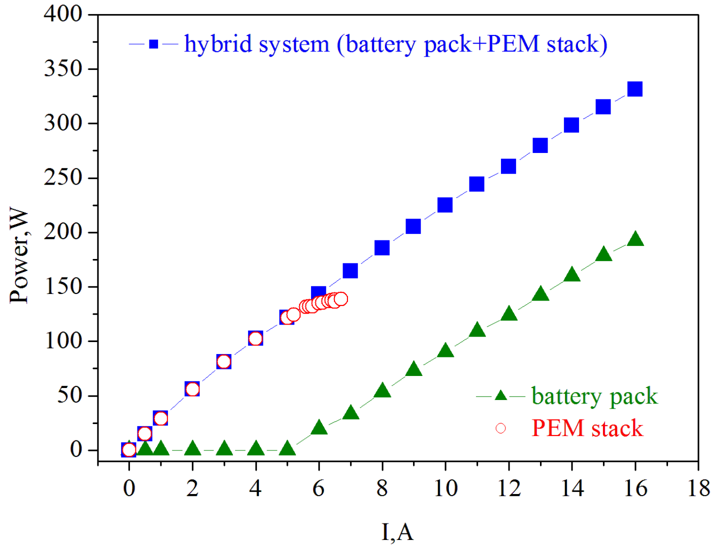
A different situation (Fig.5c) was observed during loading with I_1 = 6 A, I_2=7A or I_3=9A In this case, the voltage was stable only for a duration of 40- 20 minutes, when the Li-Po battery pack was able to complement the power deficit. After discharging the battery, the power could be derived exclusively from the FC stack, which resulted in a gradual decrease of voltage due to the dominant role of concentration polarization. This behaviour is a warning of danger when the AEROPACK system is used under high power demand exceeding 180-200 W.

Assuming the thermal efficiency of the fuel cell stack as equal to the estimated value $\eta_{th} \approx$ 0.469, one can calculate the time of flight covered without the need to refuel. These times are: ca. 1 h 39 min when the high–pressure cylinder of volume 1.1 l is loaded with H_2 to the pressure of 225 bar and 4 h 30 min when the type I cartridge of chemical fuel is a source of H_2 (in these calculations, the average power taken from the fuel cell stack is assumed to be 200 W). Therefore, the employment of the high-pressure cylinder is recommended for short test flights of the UAV, whereas longer missions require using a cartridge with chemical fuel. The use of this chemical source (usually based on sodium borohydride, $NaBH_4$) provides a prolonged, stable and sufficient supply of hydrogen fuel to the fuel cell stack even at the moments of high power demand, although it is more expensive than loading a high-pressure cylinder with H_2, [37,45]. The reliability of this chemical source operation was examined at the test facilities – the results of these measurements are presented in Fig.6.

Practically no difference was observed between the operational characteristics of the AEROPACK system supplied with H_2 from the chemical source and pressurized cylinder. Similar observations were confirmed by the other researchers [37].



a)



b)

Figure 6. (a –b) The voltage (*U*) vs. current (*I*) (a) and power (*P*) – current (*I*) (b) dependences determined for the AEROPACK hybrid system. The chemical cartridge was used as a hydrogen source.

7. SELECTION OF ELECTRIC MOTOR

The first tests of the propulsion system (motor/propeller –hybrid power unit) was done in the laboratory ground facilities with a Hacker C50 13XL brushless motor, which was recommended for a BCS Fuel Cell System in paper [46]. The BCS Fuel Cell System has similar operational parameters to the AEROPACK unit, although it uses a different cooling system (BCS: liquid, AEROPACK air). The

Hacker C50 13XL brushless motor together with the propellers used in the test are presented in Fig.7a, whereas the dependences of propeller speed on power supplied to the motor are shown in Fig.7b.

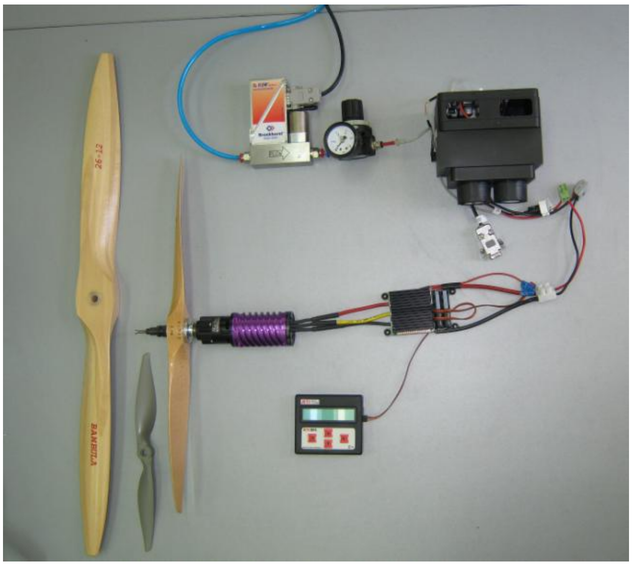


Figure 7. a) The photo of an experimental setup: the Hacker 13XL C50 brushless motor together with propellers

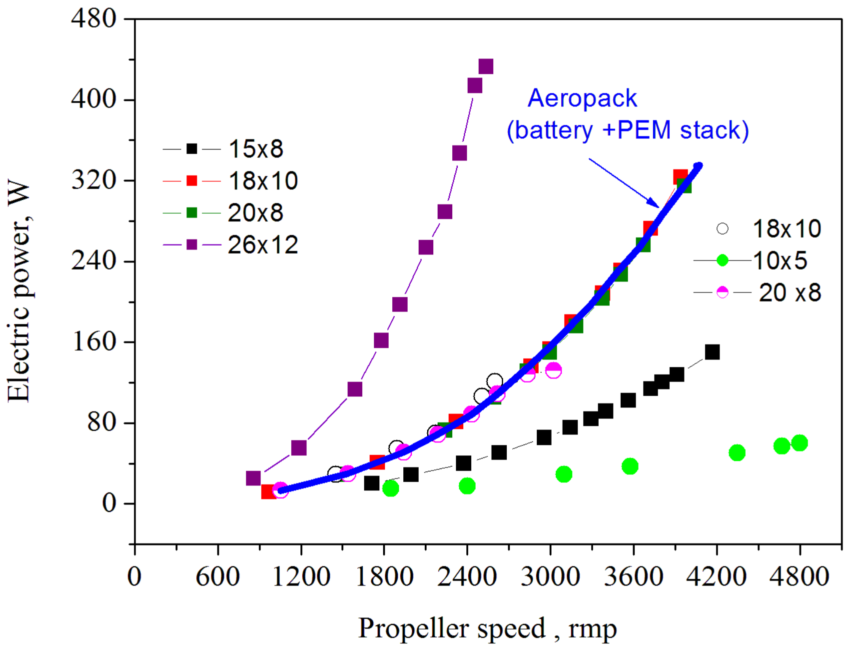


Figure 7. b) The dependences of the electric power on the propeller speed for the C50 Hacker motor with different propellers. Square and circle centered points correspond to supply with (Li-Po) 6s battery pack and AEROPACK, respectively. The size of a propeller (diameter and pitch) is given in inches next to the centered points.

Either the (Li-Po) 6s battery pack or AEROPACK hybrid system were used to power the electric motor equipped with the propeller. As can be seen in Fig.7b, the obtained data was independent of the power source within the error of measurement. The dependences presented in Fig.7b show also that the power delivered to the electric motor increases with the increase of the propeller diameter but is almost independent of the propeller pitch. That means that the thrust generated by the propulsion unit depends, first of all, on the diameter of the propeller. When the diameter of the propeller is larger the thrust will be higher. On the other hand, higher thrust results in higher loading of the propulsion unit, which leads in turn to lower propeller speed. The proper selection of propeller provides the highest possible thrust generated in the optimal operational conditions of the propulsion unit. Since the Hacker C50 13XL appeared to be too large and powerful for our UAV prototype, we have concentrated on the selection of a more appropriate electric motor with lower power and smaller dimensions.

Considering requirements arising from the conceptual design of the plane (Section 6.1) and the parameters of the AEROPACK system (Sections 6.2 and 6.3), the following constrains should be obeyed by the electric motor employed in the UAV:

- maximum power consumption – P_{inmax} = ca. 250 W;
- supply voltage – U_{dc} = 20-32 V
- rotational speed – up to n = 11000 rpm.

The analysis recommended by manufacturers during motor selections embraces also: no-load current (I_o), motor internal resistance (R_m), controller resistance (R_{cont}) and motor voltage constant (K_v = *BEMF*/*n*), where *BEMF* is the voltage induced by the motor rotating with the speed n = 1000 rpm.

Inquiries made on the commercial market for brushless DC electric motors (BLDC) showed that there were no units available which fulfilled the above conditions. In these circumstances, it was decided to select motors with lower supply voltages that can be adjusted either by using an electronic DC-DC converter or by rewinding the motor coil.

Two electric motors have been selected for this purpose: the AXI 2808/24 and the Hacker A30/28SV2. These motors have similar voltage supplies, power and dimensions. They are optimally powered by three Li-Po cells in series, which provide a maximum voltage of 12.6 V. At this voltage, a rotational speed of the unloaded AXI motor is 15 000 rpm and is slightly higher than that of the Hacker motor. When the supply voltage exceeds 20 V, which occurs when power is delivered from the AEROPACK system, the rotational speed of these motors need to be significantly reduced. It was done with the one of selected motors, namely the Hacker A30/28SV2, whose K_v voltage constant was properly increased by the variation of coil connection from delta to star to match the output characteristics of the AEROPACK unit. This way, the K_V constant was almost doubled.

The effects of these modifications are shown in Figs.8a–b. The dependences of the propeller speed n and resultant efficiency η on the current I_{dc} taken from the AEROPACK are presented in Figs. 8a-b respectively. As can be seen from the plot in Fig.8a, the assumed propeller speed n = 11 000 rpm is reached for the current of 7 A. The highest efficiency of the motor, equal to ca. 80%, is achieved for the current of 7.5 A (Fig.8b).

The above presented results show how important, and not how trivial the issue is, of the optimization of the propulsion unit consisting of fuel cell stack, auxiliary battery pack and electric motor driving the propeller. Such studies require advanced modelling, which could be helpful to specify the development directions of particular components of the system.

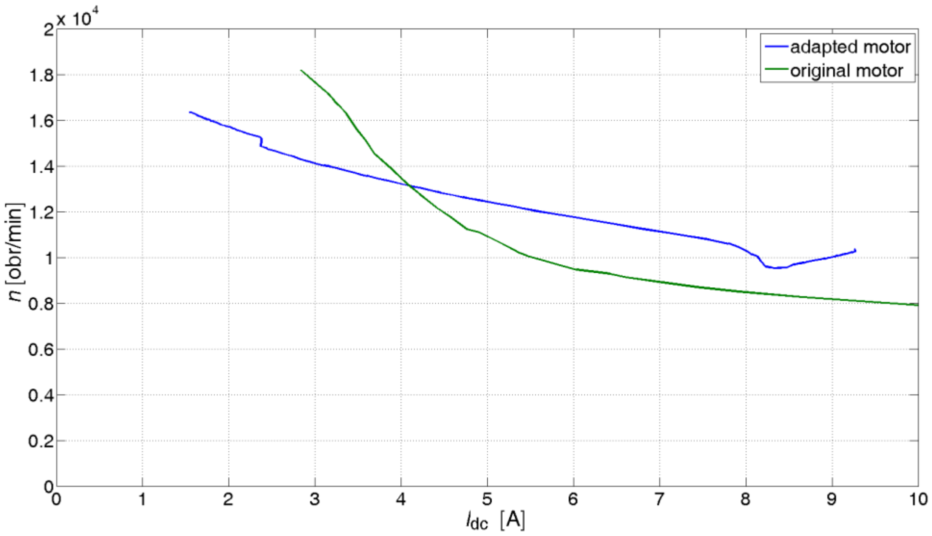


Figure 8. a) The dependences of the propeller speed *n* on the current I_{dc} taken from the AEROPACK

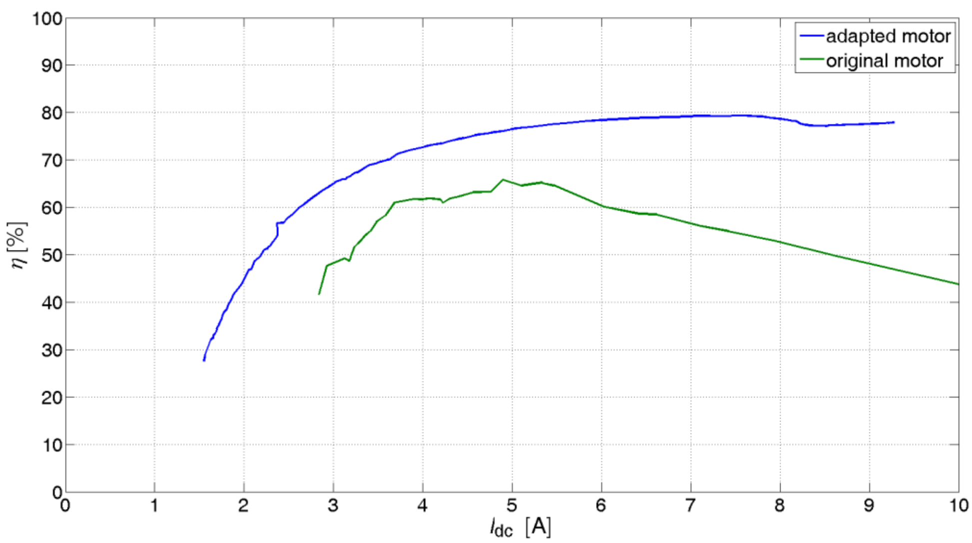


Figure 8. b) The dependences of the resultant efficiency η on the current I_{dc} taken from the AEROPACK

8. THE UAV FLIGHT TESTS

The first flight tests of the UAV prototype were performed in May and June, 2012. They were aimed, first of all, at the examination of flight characteristics of the aircraft and implementing the modifications of the plane's construction. During these tests, the UAV was equipped with a Li-ion battery pack of electrical capacity 4 359 mAh exclusively. The last flight tests of the UAV equipped with the AEROPACK hybrid system were performed in September/October 2012. The AEROPACK unit was supplied with hydrogen from the high-pressure cylinder and the duration of the tests were not longer than 0.5 h.

The photo (Fig.9a -b) illustrate flight tests during different conditions. The next tests are planned in spring 2013, where the UAV will be equipped with all the designed facilities – and the duration of flight will be prolonged to a couple of hours.

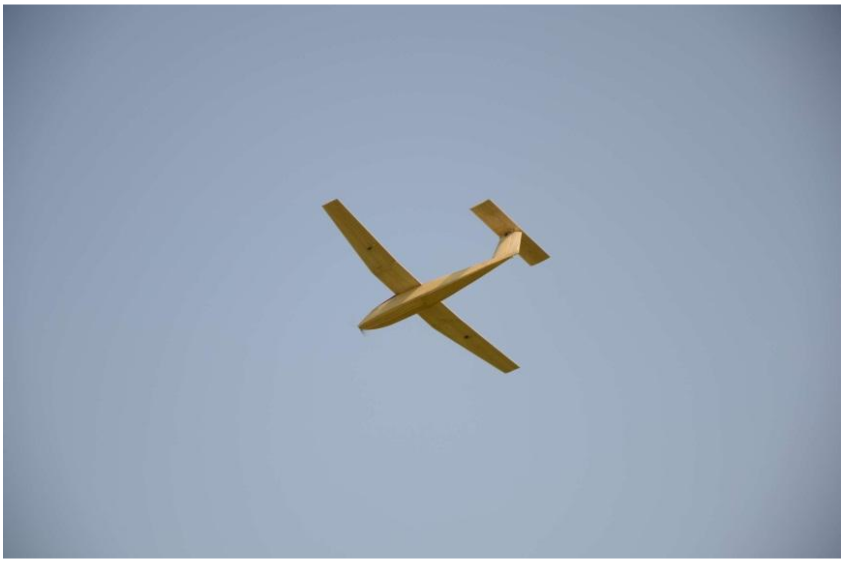


Figure 9.a) Horizontal flight during the second phase of tests in good weather conditions.

Figure 9. b) Preparing of take off during flight in good weatther conditions

9. CONCLUSION

In this paper the use of a fuel cell stack as a main source of power for small unmanned aerial vehicles was analyzed. Among several types of FCs, stacks made of polymer membrane fuel cells

(PEMFC) seem to be the most appropriate for this purpose due to accomplished high operational parameters, reliability and commercial availability. Hence, one of the commercially available PEMFC stacks, AEROPACK, was selected for the designed UAV. The stack was comprehensibly tested and characterized at the laboratory ground facilities. On the basis of the performed tests, the thermal efficiency of the fuel stack was estimated which allowed us to calculate the expected time of flight covered without the need to refuel for small composite high-pressure cylinder and chemical source of H_2. Because the AEROPACK system consisted of the fuel cell stack and battery pack, the interaction between these two electrochemical sources was examined. In addition, the electrical integration of the hybrid power system with a motor and propeller was analyzed. The selection and modification of the electric motor performed on the basis of this analysis is described in the article.

Finally, successful flight tests of the UAV prototype equipped with the AEROPACK hybrid system are described. Further improvements regarding the UAV's construction and the modification of the propulsion unit are currently under way.

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