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Power sources involving ~ 300W PEMFC fuel cell stacks cooled by different media

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Abstract Two constructions of ~300W PEMFC stacks, cooled by different media, were analysed. An open-cathode ~300W PEMFC stack cooled by air (Horizon, Singapore) and a PEMFC F-42 stack cooled by a liquid medium (Schunk, Germany) were chosen for all of the investigations described in this paper. The potential for the design and construction of power sources involving fuel cells, as well as of a hybrid system (fuel cell-lithium battery) for mobile and stationary applications, is presented and discussed. The impact of certain experimental parameters on PEMFC stack performance is analysed and discussed.

1 Introduction

Fuel cells (FCs) are electrochemical devices that directly convert chemical energy from fuel into electricity and heat. These electrochemical devices can operate as long as fuel (mainly hydrogen) and an oxidant (usually oxygen taken from the air) are supplied. Fuel cells are generally classified into two basic categories, according either to the type of electrolyte used or to the temperature of operation. In terms of the electrolyte used, five main types of fuel cells are distinguished: a) proton exchange membrane fuel cells, or PEMFCs, temperature range 30–80°C; b) alkaline fuel cells, or AFCs, temperature range 50–200°C; c) phosphoric acid fuel cells, or PAFCs, operating temperature ~200°C; d) molten carbonate fuel cells, or MCFCs, operating temperature ~650°C; e) solid oxide fuel cells (SOFCs, operating temperature 500–1000°C [1]. PEMFCs, due to their high power density, low operating temperature, and ability to start up rapidly when cold, are considered to be the most promising candidates for next-generation power sources for transportation, stationary, auxiliary, and portable applications [2,3]. Nafion-based polymer membranes are still used in PEMFCs as solid electrolytes. The main drawback of these membranes is the strong dependence of their protonic conductivity on water content and temperature. This requires continuous monitoring of temperature and humidity during single-PEMFC and PEMFC-stack performance [4]. However, In platinum catalysts of electrode materials, which become passivated in catalytic activity there is a strong need for cleaning in the reformation process of kerosene in order to achieve a tolerably low CO content (in the ppm range) for the fuel cell. Therefore, one of the

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main tasks in the future should be to develop compact reformers and ways to reduce fuel poisons such as CO and sulphur. Until these reforming problems are solved, PEMFCs are suited only for applications where the use of pure hydrogen as fuel is feasible and acceptable. The high price of platinum and limited resources make it necessary to find new, cheaper catalysts with high tolerance for impurities [5,6].

A PEMFC fuel cell stack consists of many single cells, stacked so that the cathode of one cell is electrically connected to the anode of the adjacent cell. In this way, exactly the same current passes through each cell. The key aspects of a fuel cell stack design are: uniform distribution of reactants to and inside each cell; maintenance of the required temperature in each cell; minimum resistive losses made possible through choice of materials, configuration; uniform contact pressure; mechanical sturdiness (ability to withstand internal pressure, including thermal expansion, and external forces during handling and operation, including shocks and vibrations) [7,8].

A PEMFC fuel cell is very sensitive to the flow rate of the reactants. Each cell in the stack must receive approximately the same amount of reactant gases. Uneven flow distribution would result in uneven performance of the cells. Water and heat are the by-products of fuel cell operation, and the supporting system must include the means for their removal. It is possible to re-use water or heat, at least partially – for example, for humidification of the reactant gases. The PEMFC stack is the main part of a fuel cell system. In designing power sources involving PEMFC stacks, supporting equipment is necessary for operation. A fuel cell system typically involves the following subsystems: oxidant supply (oxygen or air), fuel supply (hydrogen or hydrogen-rich gas), heat management, water management, power conditioning and instrumentation, and controls [9,10]. During PEMFC stack operation, heat, as a by-product occurring in the course of electricity production, must be effectively removed from the fuel cell system. The most favourable operating temperature range for existing PEMFCs is usually 60–80°C. A higher temperature can significantly exacerbate the degradation of the membrane and the catalyst and reduce the stack's performance. On the other hand, a lower temperature is not favourable for the reaction kinetics and may also cause flooding due to lower water saturation pressures at low temperatures, which is a major concern from the water management perspective. Effective cooling is critical for safe and efficient operation of PEMFC stacks [11-13]

Despite advanced interdisciplinary research and development work on various designs of fuel cell power generators, certain issues concerning their operation, including the potential for and barriers to their application in integrated electrical systems have not been fully recognised or explained, even in regard to commercially available PEMFC stacks [14,15]. It must be emphasised that the fuel cell stack market in EU countries is thriving; these products can be easily bought and delivered to their intended recipients. Moreover, any increase in the use of fuel cell technology in Poland requires acquisition of necessary knowledge concerning electrochemical sources of energy (fuel cells, batteries and accumulators, supercapacitors), their advantages, and operating capacities and applications. Therefore, training of specialised staff should cover interdisciplinary procedures, enabling staff members to learn about the design and operating principles of fuel cells, the potential for constructing fuel cell power generators, and their research methodology, as well as specifying the potential for and barriers to their use within specific technical applications [16].

In this study, the performance of power sources involving a 300-W PEMFC stack cooled by different media was considered. Special focus was placed on the effect of experimental conditions on the performance of designed PEMFC stacks. The potential for modification of electrical parameters, as well as for reduction of the mass and cost of fuel cell systems, was also analysed in this study.

2 Experimental

2.1 Selection of types of PEMFC stacks with ~300 W electric power

Two commercially available PEMFC stacks were selected for the construction of an electric generator involving fuel cell technology.

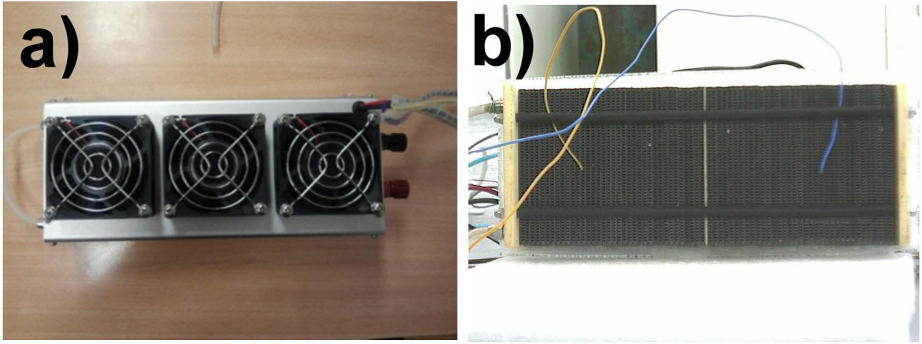

Fig. 1. Photo: a) the initial Horizon H-300 PEM Fuel Cell without modification and b) H-300 PEM Fuel Cell with modification - divided into two modules of 35 cells each, using a gold-plated board.

The first was the Horizon H-300 PEM Fuel Cell, a 300-watt (Fig. 1a), air-fed/air-cooled, self-humidified hydrogen fuel cell suitable for many medium-scale projects and uses. The open-cathode compact PEMFC stack permitted the performance of some necessary modifications aimed at adapting the electrical parameters of the stack to the requirements of the electrical system. The first modification was aimed at lowering the starting voltage of the PEMFC stack. The initial H-300 PEMFC stack was divided into two modules of 35 cells each, using a gold-plated board (Fig.1b) with channels for hydrogen supply as an electrical separator. The modules operated in parallel mode. The gas tightness of the new elaborated stack was checked and all hydrogen leakage was eliminated. The potential for the construction of a hybrid power system (fuel cell battery) was also considered. The new elaborated self-humidifying PEMFC stack was connected with a 6S lithium ion battery pack for peak energy demand and energy storage for safety and stack start-up purposes. The element connecting the cell stack and the LiPo battery is a charge-discharge control system, which consists of two subsystems. The charge subsystem enables the collection of excess electricity during lower demand periods (horizontal flight or descending especially in UAV applications). This system was built on the basis of a high-performance DC-DC converter limiting the charging voltage to the LiPo battery pack to a safe range (4.2V per cell, CV mode) and a charging current. The discharge subsystem can use energy stored in the battery. In this mode, the current flows through the diode in the reverse direction. In addition, the LiPo battery pack can be equipped with an active balancer evening the charge level of individual cells in a package. PEMFC stacks were tested with a laboratory electronic load (Dynaload XBL 50-150-800). Dry hydrogen was supplied from a laboratory installation under a pressure of 0.4 bar.

During the operation of two series-connected PEM fuel cell stacks, the distribution of temperatures at the surface of each stack was recorded without contact, using a ThermoTracer H2640 thermographic camera (manufactured by NEC) with a thermographic detector (also an NEC product) with dimensions of 640×480 pixels to record the temperature with a thermal resolution of 0.03°C. During the measurements, the temperature of the air in the laboratory was T_a=20.1°C; the emissivity ratio of the camera was set to ε=0.91. Thermal images recorded as the result of measurements were processed and analysed using Thermography Studio Professional, a software program dedicated to this camera.

The second type was a 360-W PEMFC stack with a closed cathode, cooled by a liquid medium (Schunk, Germany).

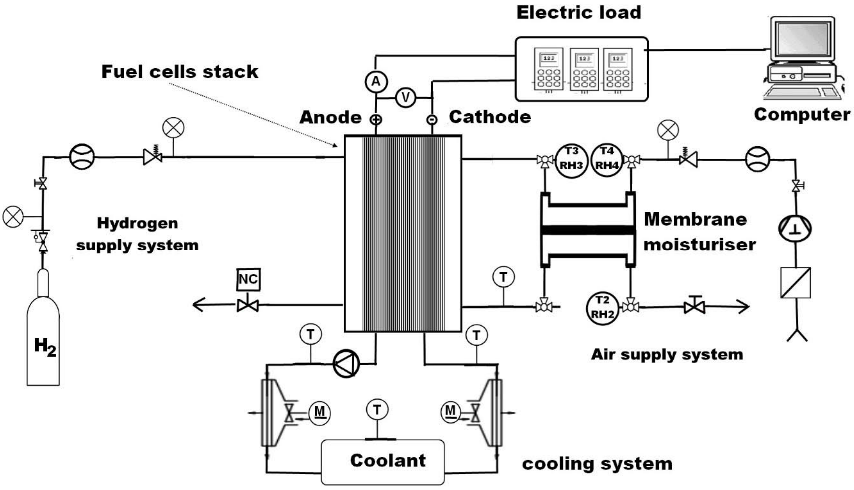

Fig. 2. Schema of an experimental setup designed to characterise an FC-42 PEMFC stack cooled by liquid media.

Fig.2 present a schema of an experimental setup designed to characterise an FC-42 PEMFC stack cooled by liquid media. The fuel cell stack was powered by high-purity hydrogen. The hydrogen dosing system was equipped with a pressure regulator with a control manometer, which lowered the pressure to 0.3 bar, as required by a fuel cell stack. The amount of hydrogen fed to the PEMFC stack was monitored using a Bronkhorst flow measurement valve. At the hydrogen outlet of the PEMFC stack, there is an electrically controlled normally – closed valve functioning as a purge valve whose primary function is to rinse the anode component of the cell during the start, finish, and operation of the pile through periodic opening and introduction of hydrogen into the surroundings. The fuel cell stack's cathode was powered with air introduced by a dry-running air compressor (model ACO-006, 75 W, efficiency 110 l/min) through a system of filters, pressure regulators, and rotameters to measure the flow.

3 Results

Electrically powered small unmanned aerial vehicles (UAVs) in particular are already suited for the application of PEMFC fuel cells. By replacing their batteries either partially or totally with a fuel cell system, flight times can be significantly extended [17].

Each galvanic cell (including a single fuel cell) and fuel cell stack is characterised by maximum power, represented by a pair of (voltage-current) max parameters. For some types of galvanic cells, this point may not be observed in power-current dependence curves if its position is far outside the range of useful voltages or currents. In the case of fuel cells, the position of the (voltage-current) max point is usually clearly marked and plays an important role in the performance of the generator. Gradual loading of a fuel cell stack leads to a self-regulating change in work conditions (voltage drop, current increase, increase in the amount of hydrogen fuel used), which leads to an appropriate increase in the power drawn from the stack according to rising need. This will remain in effect until the maximum power point is achieved, after which a rapid fall in the power supplied by the cell stack is observed despite the increasing load current. The shortage created in the power balance of the drive unit may lead to a loss of aerodynamic lift, with dramatic consequences for the plane [18].

3.1 Performance measurements PEMFC stack air-cooled.

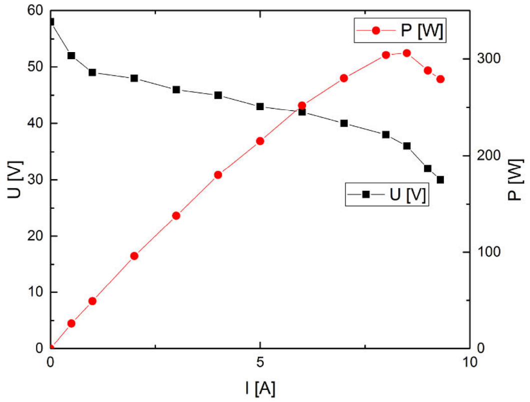

Fig. 3. Current voltage and current-power curves of unmodified H300 fuel cell stack.

In Fig.3, the) current (I) - voltage (U and current (I) – power (P) relationships of the original 300-W H-stack are presented. It was found that the maximum of power output (P_{max})~300 W, was recorded for the following pair of electrical parameters: I=8.4A, U=36.5V. Based on recorded characteristics, the performance of a PEMFC stack is recommended to be close to the electrical parameters recorded for P_{max}. Unfortunately, the open circuit voltage U for I= 0A was close to 60V; all recorded voltage values under load are higher than 35V. In the case of the application of the original H-300 PEMFC stack as a main power source for supplying small electrical brushless (AXI, Czech Republic or Hacker Germany) in small unmanned aerial vehicle (UAV) construction, these values are higher than the requirements of the electric motor management controller.

The first electrical modification was aimed at lowering the starting voltage of the PEMFC stack. The initial H-300 PEMFC stack was divided into two modules (35 cells in each module) using an electrical separator. Gold-plated board (Fig. 1b) with channels for hydrogen supply was used as an electrical separator. The modules operated in parallel mode. As can be seen in Fig. 4, reductions in open circuit voltage (OCV) were obtained, as well as in the values of voltage under load. In this case, the voltage and current values are suitable for most electric brushless motors applied in UAV technology.

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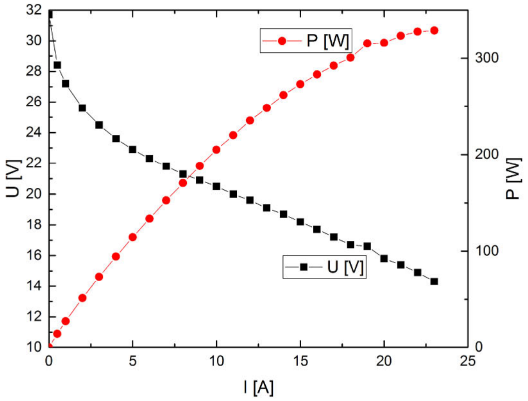

Fig. 4. Current voltage and current-power curves of modified 300W fuel cell stack.

In the case of instantaneous power deficit, one frequently used solution is the employment of an auxiliary unit consisting of a storage battery pack or super-capacitor system. In this study, a PEMFC stack was connected in parallel with a lithium polymer battery pack and tested. It is extremely important to determine the voltage-current and power-current characteristics of the complete system to be sure that the above-mentioned power deficit does not occur, even in unusual conditions of aircraft operation.

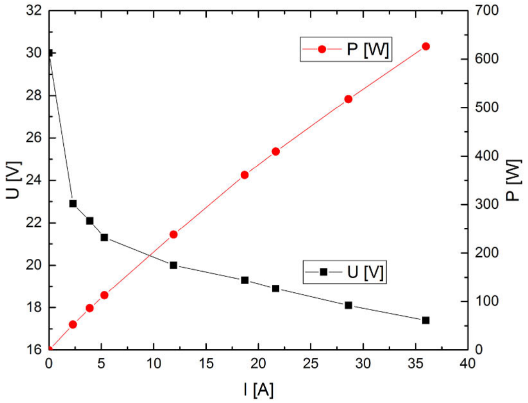

Fig. 5. Current voltage and power curve of hybrid fuel cell – lithium battery system

In Fig. 5, the U-I and P-I dependences for a hybrid system (PEMFC stack + battery system) were determined. An increase of power density up to 600 W was recorded. In the case of a hybrid power system, the P_{max} of this source was not visible.

The results of the electrical investigation of a PEMFC stack with an open cathode indicated that, in this type of construction, it is relatively easy to modify a PEMFC stack to fit the fuel cell as a power source to the requirements of electrical motors (24–32 V) typical of UAV construction. The reduction of the total mass of the stack, which is also a crucial parameter, from 2100 to 1300 g was achieved as well in the newly modified construction.

Fig. 4a presents the thermographic image of temperature distribution on the surface of the PEMFC stack on the air inlet side, recorded on the bench during measurement of the stack while operating under electricity load.

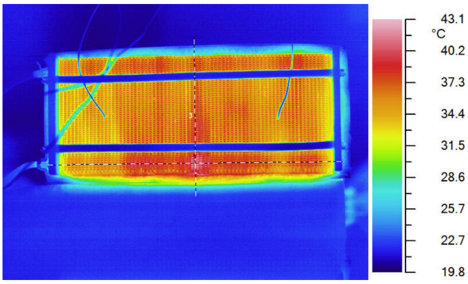

Fig. 6a. Thermographic image of temperature distribution on the PEMFC stack on the air inlet side

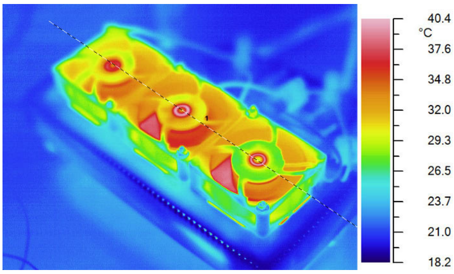

Fig. 6b. Thermographic image of temperature distribution on the PEMFC stack on the fans side

Based upon analysis of the thermographic image (Fig. 6a), two horizontal dark blue stripes are visible in the foreground (relative to the stack of PEM cells heated by their operation). These are two metal rods, extending beyond the stack, which serve to compress the individual fuel cells making up the stack, and thin thermocouple wires used to control the temperature of individual FC stacks. During PEMFC operation under load, the temperature, which varies within a range of approximately 35 to 40°C, is lower on the left side. This is because on this side, located at the bottom, was a supply (inlet) of fresh gaseous hydrogen at ambient temperature, with an outlet at the top from the anode space where reaction products were discharged during periodic purges ('purge'). In Fig. 6b, temperature is distributed along a line passing through the centres of the three fans used to cool the FC stack. It can be seen that the highest temperature (approximately 40°C) is attained by the centres of the fan rotors, under which both bearings (on which they are grounded) are located, and by the windings of the DC electric motors they are driven by. These results clearly indicate that all modified PEMFC stacks operate within a safe temperature range (30-40^{o}C). No unexpected local increases (> 60^{o}C) of temperature were observed in the modified PEMFC stack.

3.2 Performance measurements PEMFC stack liquid-cooled supplied with dry or humidified air.

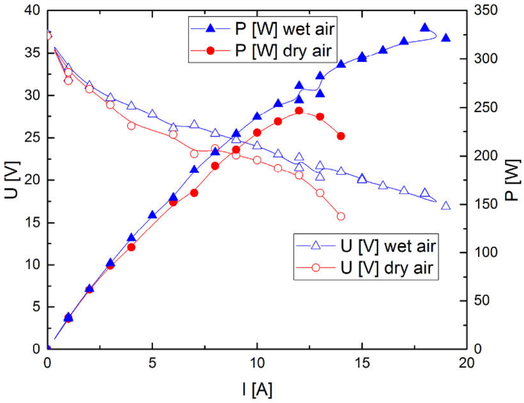

Fig. 7. The family of U-I and P-I curves recorded for an FC-42 PEMFC stack supplied with dry or humidified air

In Fig. 7, the (U)-current (I) and power (P)-current (I) curves are recorded for an FC-42 stack supplied with dry or humidified air.

Direct comparative analysis of U-I and P-I curves obtained for an FC-42 stack fed by dry or humidified air reflects the difference in electrical performance of the investigated power sources. Analysis of U-I and P-I dependencies enabled us to distinguish three areas of electrical response.

(1) In the first area of applied current load, the dominance of activation losses is visible. Although it was noted previously that practically the same value of open circuit voltage U1=U2 was obtained (U=37V, I=0A), progressive switch on electrical loading of a PEMFC stack with small currents (from 1 to 2 A) leads to a gradual decrease in voltage values. In these measurement conditions, no significant differences in the electrical response of the PEMFC stack were observed.

(2) In the second area of switch on current load to the PEMFC stack, where the current I varies from 3 to 12A, the difference in the electrical power output of the energy generator involving the PEMFC stack becomes more visible. Initially, when the current load increased to more than 5A, slightly lower values of voltage were observed for a PEMFC stack fed with dry air than for one fed with humidified air. In these test conditions of applied current load, near-linear dependency of U-I was obtained. In this area, the main source of energy losses is ohmic polarisation. An increase of resistance due to the polymer membrane is responsible for the occurrence of these losses. The presence of humidity in air can improve protonic conductivity in a Nafion membrane, due to humidification of the polymer. These electrolytes are very sensitive to H_2O content in the cell.

(3) The third area of curves U=f(I) corresponds to current load I>12A for a PEMFC stack supplied with air without humidification and I > 18 A for a stack supplied with humidified air. In these experimental conditions, the maximum power (P_{max}) output of the power sources was obtained. It was found that in the case of an FC-42 supplied with dry air, the maximum power output P_{max} was observed for the pair of values I=12A and U=27V (P_{max}=246W), but in the case of an FC-42 stack supplied with humidified air, improved parameters were recorded (P_{max}=332W, I=18A). Above the P_{max} a rapid voltage drop was recorded due to an increase in the current load. Switch–on of higher values of current load is not recommended for PEMFC stacks, due to not only the consequent reduction of electrical power but also the potential introduction of irreversible changes in the PEMFC structure and destruction of the cells.

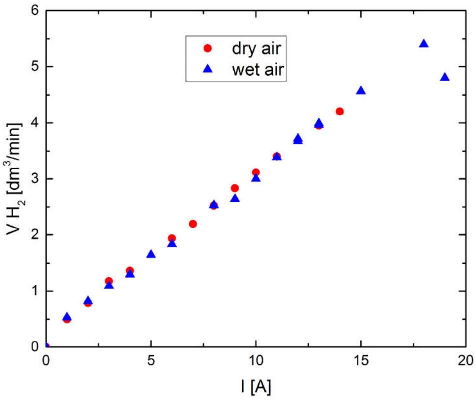

Fig. 8. Dependency of the amount of hydrogen consumed by the Schunk FC-42 fuel cell stack vs the current generated by the investigated power source. The PEMFC stack was supplied with humidified air (A) or dry air (B).

In order to determine the amount of hydrogen consumed during operation of the PEMFC FC-42 stack, the flow rate of hydrogen was measured using a mass flow meter. Fig. 8. shows the dependency of the amount of hydrogen consumed by the Schunk FC-42 fuel cell stack vs the current generated by the investigated power source. The measurements were made in analogous conditions. The PEMFC stack was supplied with humidified air (A) or dry air (B). Based on this analysis, it can be concluded that the amount of hydrogen utilised as a fuel for supplying a PEMFC stack rises with increasing current produced by the stack. For I=18A, maximum hydrogen consumption was found to be 5.5 dm^3/min.

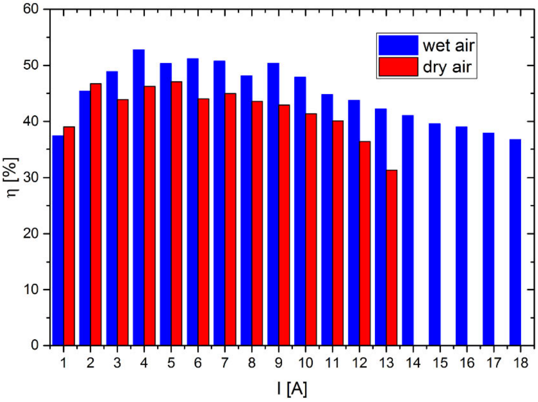

Fig. 9. Comparison of the electrical performance obtained from the PEMFC FC-42 stack supplied with dry or humidified air.

However, a direct comparison of the levels of power output (P_{max}) obtained from the PEMFC FC-42 stack supplied with dry or humidified air, respectively, indicated a difference in the electrical performance of the investigated power sources (Fig. 9.). The highest power output of the PEMFC FC-42 stack was recorded when humidified air was introduced into the cathode chamber. The observed increase in the electrical power of the PEMFC stack was caused by appropriate moisturisation of the polymer electrolyte with water introduced along with air into the cathode chamber.

4 Conclusion

Two electrical generators involving ~300W PEMFC stacks, cooled by air or by a liquid medium, were designed and investigated. Their performance, along with the potential for modification of their electrical parameters and simplification of the construction of power sources, is presented. It was found that in the case of an open-cathode stack, the modification of electrical parameters and construction aimed at the reduction of mass is simpler when compared to a similar electrical generator involving a PEMFC stack cooled by liquid media. The potential for the construction of a hybrid system (battery-fuel cell stack) is also demonstrated. The elaborated hybrid system, thanks to its customised electrical parameters as well as its compact light construction, seems suitable for transport applications (small UAVs, bikes, etc). On the other hand, power sources involving PEMFC stacks cooled with a liquid medium, due to their additional cooling system, seem to be better suited for stationary applications (UPS systems).

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References

1. K. Kordesch, G. Simader, *Fuel Cells and their applications*, (VCH Publisher, Inc, New York, USA, 2001)
2. M. Oszcipok, M. Zedda, D. Riemann, D. Geckeler, J. Power Sources **154**, 404 (2006)

3. Y. Wang, K.S. Chen, J. Mishler, S.Ch. Cho, X.C. Adroher, Applied Energy **88,** 981 (2011)
4. P.P. Lopes, K.S. Freitas, E.A.Ticianelli, Electrocatalysis **1,** 200 (2010)
5. S.B. Fabry, L.Dubau, Y. Ahmad, K. Guerin, M. Chatenet, Electrocatalysis **6**, 521 (2010)
6. X. Wu, B. Zhou, J. Power Sources **324**, 804 (2010)
7. Z.M. Huang, A. Su, Y.Ch. Liu, Energy **72,** 547 (2014)
8. S.W. Jeon, D. Cha, H.S. Kim, Y. Kim, Applied Energy **166,** 165 (2016)
9. D. Chu, R. Jiang, J. Power Sources **83,** 128 (1999)
10. N. Sammes, *Fuel Cell Technology: Reaching Towards and Commercialization*, (Springer –Verlag London 2006)
11. Ch.Y. Chen, K.P. Huang, W.M. Yan, M.P. Lai, Ch.Ch. Yang, Int. J. Hydrogen Energ. **41,** 11784 (2016)
12. M.G. Santarelli, M.F. Torchio, M. Calı, V. Giaretto, Int. J. Hydrogen Energ. **32**, 710 (2007)
13. G. Zhang, S. G. Kandlikar, Int. J. Hydrogen Energ. **37**, 2412 (2012)
14. Ó. Gonzalez-Espasandin, T.J. Leo, E. Navarro-Arévalo, The Scientific World Journal **2014**, 497642 (2014), Review Article Fuel Cells: A Real Option for Unmanned Aerial Vehicles Propulsion http://dx.doi.org/10.1155/2014/497642
15. R. Agarwal, F. Collier, A. Schaefer, A. Seabridge, *Green Aviation* (John Wiley & Sons, 2016)
16 C. Harms, F. Köhrmann, Al. Dyck, Solid State Ionics **275**, 75 (2015)
17 J.M. Krawczyk, A.M. Mazur, T. Sasin, A.W. Stokłosa, Transactions of the Institute of Aviation **4**, 49 **(**2014)
18. M. Dudek, P. Tomczyk, P. Wygonik, M. Korkosz, P. Bogusz, B. Lis, Int. J. Electrochem. Sci., **8,** 8442 (2013)