Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 1102 – 1108

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Performance evaluation of Microbial Fuel Cells fed by solid organic waste: parametric comparison between three generations

R.A. Nastro[a], N. Jannelli[b], M. Minutillo[a], M. Guida[c], M. Trifuoggi[d], L. Andreassi[e], A.L. Facci[f], V.K. Krastev[f] and G. Falcucci[e,*]

[a] Dept. of Engineering – University of Naples "Parthenope", Centro Direzionale - Isola C4, 80143 Naples
[b] A.T.E.N.A. scarl, Centro Direzionale - Isola C4, 80143 Naples
[c] Dept. of Biology – University of Naples "Federico II", Via Mezzocannone 16 80134 Naples
[d] Dept. of Chemical Sciences – University of Naples "Federico II", Complesso Monte Sant'Angelo 21, 80134 Naples
[e] Dept. of Enterprise Engineering "Mario Lucertini" – University of Rome "Tor Vergata", Via del Politecnico 1, 00134 Rome
[f] DEIM – University of Tuscia, Largo dell'Università snc, 01100 Viterbo

Abstract

In this paper, the results of three generations of reactors for the direct conversion of the Organic Fraction of Municipal Solid Waste (OFMSW) in electrical energy are presented. The different generations corresponds to the prototype realized in the Energy Lab of the University of Naples "Parthenope" and have been monitored along a period of over three years in terms of polarization and power curves, in order to assess the feasibility of Microbial Fuel Cell as a promising source for future, sustainable energy generation.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords:

1. Introduction

The search for new energy sources able to grant efficiency and sustainability has become a central topic for research efforts all over the world, [1-7]. Microbial fuel cells (MFCs) have emerged in recent years as promising contributors to the transition to a low-carbon society, being able to mitigate emissions of greenhouse gases, and reduce the dominance of fossil fuels. Probably the most important reason that makes this technology so attractive is related to its working principle: MFCs, in fact, can generate electricity through the catalytic activity of exo-electrogenic bacteria involved in the anaerobic oxidation of organic substrates acting as low grade fuels [8-11]. Even if they energy produced by MFCs is relatively low if compared to other fuel cell technologies, they can produce chemical energy from several classes of wastes, with the potential to effectively and directly convert into electrical energy several non-purified organic substrates.

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: author@institute.xxx .

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.472

This last aspect is of a particular importance if we think about that the large part of municipal solid waste is represented by organic matter, and its recovery for reuse is so challenging that an energy recovery process is often preferred, due to the chemical energy content [12].

In this scenario, Microbial Fuel Cells (MFCs) can solve some of these problems, because they actually are a valid alternative for distributed and direct conversion of organic waste to electricity [13-15]. Moreover, operating at room temperature and pH close to neutrality [16, 17] MFCs could be one of the most interesting technology for application in remote areas. Other key aspects are that MFCs possess a high-energy transformation efficiency since it converts the chemical energy stored in substrates into electricity directly and do not need energy input for aeration, which lowers operational costs [18, 19].

As biomass-based systems, MFCs (like other Bioelectrochemical Systems) are considered carbon neutral: the bio-transformation of organic matter into chemicals through microbial metabolism, in fact, prevents the primary production of CO_2 emissions. Moreover, MFCs do not involve CH_4 production and combustion, as opposed to traditional anaerobic digestion plants. Accordingly, remarkable features can be observed: the direct electrical power production, the conversion of the chemical energy contained in any form of biomass, low environmental impact, low operating temperatures and simple architectures [20].

All these characteristics, together with the environmental advantages ingrained with this technology are supposed to largely overcome the costs for MFC development and implementation [22].

Many literature studies, even performed by the Author themselves [22-24] demonstrate that to completely exploit the MFCs potentialities, an experimental activity is still needed. To this aim, three different prototypes for the direct conversion of the Organic Fraction of Municipal Solid Waste realized in the Energy Lab of the University of Naples "Parthenope" are investigated and discussed. Results demonstrate that this technology could represents a real solution for OFMSW "green" treatment.

2. Materials and Methods

2.1. First Generation

In the First Generation experimental campaign, we realized three single chambered and membraneless MFCs by modifying a glass jar with airtight top, described in [25]. For each MFC, two graphite plates (AXF-5Q, POCO Graphite Inc., Texas, USA) with a surface area of 67 cm^2 were used as electrodes. The cathode was directly exposed to ambient air. An inorganic siliconic cement (Wurth Black 250, Wurth Italia Srl, Bolzano, Italy) was used to seal the reactor. As stated at the beginning, in order to investigate the influence of oxygen availability in the chamber as well as the electrodes distance, 3 MFCs were set-up: 1) MFC1 with a microaerophilic environment and a distance between the electrodes of 5 cm; 2) MFC2, with a anoxic environment and the electrode distance as in MFC1; 3) MFC3, with an anoxic environment and a distance between electrodes of 2.5 cm. All MFCs operated in batch conditions at 25°C for 6 weeks.

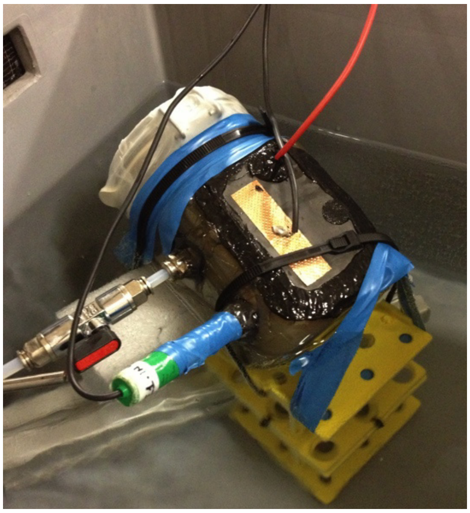
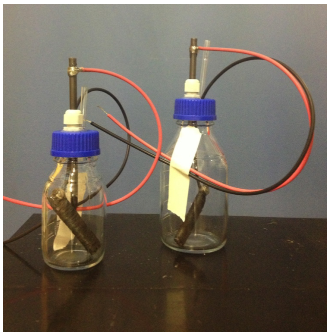


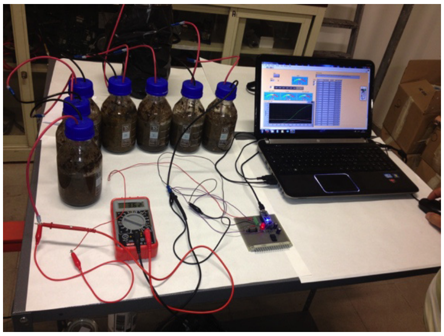
Figure 1: First Generation MFC reactor in thermostatic bath.

2.2. Second Generation

The second generation reactors were made by using glass bottle for Lab use, as shown in Fig. 2.



(a)



(b)

Figure 2: Second Generation MFC reactors.

In this case, the anode and the cathode were realized by means of the lead of a black wax crayon; the cathode was fixed to the bottle plastic cap by means of the same inorganic siliconic cement (Wurth Black 250, Wurth Italia Srl, Bolzano, Italy) adopted for the first-generation reactor.
The anode, on the other side, was coated by means of carbon fiber, in order to increase the total surface available for electro-active bacteria. In order to assess the reproducibility of the experiment, several reactors have been realized, as shown in Fig. 2b.

2.2. Third Generation

Tubular MFC bioreactors were realized by using standard 50 mL polypropylene Falcon test tubes, supplied by BD Corning Inc. (Tewksbury, USA), sterile and suitable for biological cultures; such reactors were adapted from [22, 26]. One 20 mL Falcon tubes was mounted on each 50 mL Falcon tube and was used to sample the organic feedstock and to monitor pH (see Fig. 3).

The electrodes were made by carbon-fiber anode brush, realized with a high strength carbon fiber from FIDIA s.r.l. (Perugia, ITALY) and unpolished stainless steel wire (ASTM A313) with 0.5 mm section, while for the cathode a porous ceramic disk was developed starting from graphite powder type GK 2 Ultra-fine, by AMG Mining AG (Hauzenberg, Germany). The brush anode had an estimated surface area of 0.22 m^2/g while the cathode disk had a surface area of 60.75 m^2/g, [26]. The electrodes were placed at a distance of ~ 3 cm. Due to the horizontal layout, in order to prevent the leackages through the porous cathode, a standard Nafion 117 membrane by DuPont Inc. (Richmond, USA) was used to seal the Falcon test tube.

2.3 Feedstock Preparation and Data Acquisition System

In all the three experiments, the feedstock was based on the Organic Fraction of Municipal Solid Waste (OFMSW), in particular on vegetable and fruit residues.

According to the three generation, different preparations have been carried out for the organic feedstock. In particular:

- 1^{st} generation: 2.5 kg of fresh solid organic residues (80% leaves,10% twigs, 10% shrub wood) were collected in a treatment plant in Naples district (southern Italy), processing the organic fraction of municipal waste. The organic waste was stored at 4°C for 24 hours before the analysis. Then, 600 g of waste were added to a solution of 400 mL of sterile Reverse Osmosis (RO) water, 45 mL of sodium acetate and 0.1 g of glucose. The obtained slurry was firstly homogenated by a Stomacher 400 Circulator (Seward, Worthing, UK) for 20 seconds at 230 bpm, then anaerobically incubated at 15±2°C for 7 days to enrich the fuel with products deriving from cellulose and lignin fermentation, according to Rodrigo et al., 2009. Thereafter, 460 mL of slurry (containing an overall amount 280 g of solid waste) were added to the cell. The pH of the slurry was adjusted to 4.8 by adding 450 mL of Na_2CO_3 (0.1 M) and 100 mL of KOH (1M). Volume was adjusted to 1 L by adding sterile RO water.

- 2nd generation: as for the previous experiment, 2.5 kg of fresh solid organic residues (80% leaves, 10% twigs, 10% shrub wood) were collected in a treatment plant in Naples district (southern Italy), processing the organic fraction of municipal waste. For these reactors, however, the organic waste did not receive any other treatment and it was diluted by means of fresh water in a 1:1 weight proportion.
- 3rd generation: Apples, pumpkins, chickpeas and zucchini in a 1:1:1:1 ratio were used to prepare a slurry by mechanically mixing the vegetable residues with water, according to two solid-to-liquid ratios: 1:1 and 1:3. No other treatments were employed for the organic substrate.

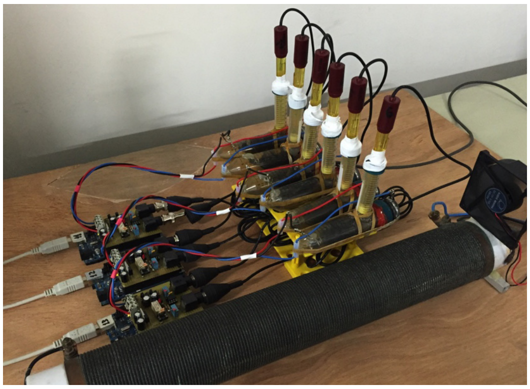


Figure 3: Third Generation MFC reactors. The Figures shows 6 reactors with their respective ARDUINO board and, at the bottom, the large electrical resistance used to keep the ambient temperature at T = 25° ± 0.5°C

The data collection hardware was based on the Arduino board MEGA 2560, (see Fig. 3) composed by a load array (for polarization curve acquisition) with 6 resistors, ranging from 10^6 Ω to 10 Ω. The software for data acquisition was ad-hoc developed in our Lab with LabVIEW Interface For Arduino, (LIFA) package.

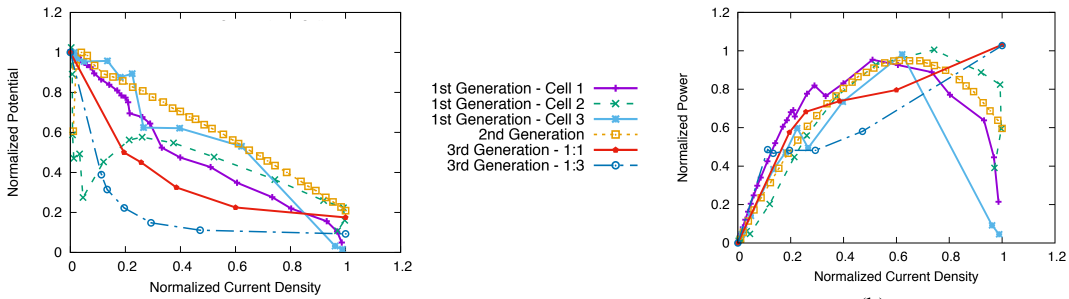
3. Results, Discussion & Future Perspective

The performance of the different generations of MFC's were evaluated in terms of polarization and power curves, acquired by means of our ARDUINO-based system. Figure 4 (a) and (b) report the trends of the polarization and power curves (respectively) for the three generations of MFC's. Due to the differences in layouts, feedstock and electrodes, such trends have been normalized according to their respective maximum values, in order to make the data directly comparable.

From the comparison, it is possible to see that the first and second generation behaved in very similar ways, even though in the second generation, the performance were much higher due to the presence of the wax crayon, which actively participated to the reaction (at the end it was completely digested).

The third generation, on the other hand, provided very different trends, due to a lower internal resistance, achieved thanks to the reduced distance between the electrodes and to the adoption of a carbon fiber brush for the anode, which provided a higher surface-to-cell-volume ratio, compared to the previous layouts.

Due to the lower value of internal resistance, the third generation has been chosen as the basis for the study of scaled-up reactors for industrial purposes. According to our results, ongoing investigations are aimed at characterizing the microbial strains that are present in the organic substrate, in order to understand their characteristic behavior during the experiment and enhance their performance. Besides this, a numerical model based on the Lattice Boltzmann Method [27-31] has been developed, coupling the thermo-fluid dynamics and electrochemistry inside the reactors, in order to predict the cell performance and inner conditions, according to the different employments.



(a) (b)

Figure 4: comparison between the performance of the three generations of MFC's: (a) polarization curves and (b) power curves.

5. Conclusions

In this work, we have explored the power performances of three generations of Microbial Fuel Cells realized in the Laboratory of Energy Systems, at the University of Naples "Parthenope".

The different operating conditions and the heterogeneous employed substrates highlight the versatility and the reliability of MFC technology. According to our results, we measured that increasing the surface of the electrodes in respect to the reactor volume dramatically increases the cell performance in terms of generated power. Ongoing studies are devoted to better understand reactor behavior, in order to scale up MFC's for industrial applications.

Acknowledgements

This work was supported by the Italian Government Research Project PON03PE_00109_1 "FCLab - Sistemi innovativi e tecnologie ad alta efficienza per la poligenerazione", with Prof. Elio Jannelli as the Scientific Responsible.

The precious contributions by Prof. Elio Jannelli for the scientific discussions and by Dr. Giovanni Erme and Dr. Enzo De Santis for reactor realization are kindly acknowledged.

References

[1] Cleveland, C.J. and Morris, C. Dictionary of Energy, *Elsevier* 2014.

[2] Cappa, F., Facci, A.L. and Ubertini, S. Proton exchange membrane fuel cell for cooperating households: A convenient combined heat and power solution for residential applications. *Energy* 2015 90: 1229-1238.

[3] Facci, A.L., Andreassi, L., Martini, F. and Ubertini, S. Comparing Energy and Cost Optimization in Distributed Energy Systems Management, *J. Energ. Resour.-ASME* 2014 136(3): 032001.

[4] Facci, A. L., Cigolotti, V., Jannelli, E. and Ubertini, S. Technical and economic assessment of a SOFC-based energy system for combined cooling, heating and power. *Appl. Energ.* Available online 5 July 2016, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2016.06.105

[5] Falcucci, G., Jannelli, E., Minutillo, M. and Ubertini, S. Fluid Dynamic Investigation of Channel Design in High Temperature PEM Fuel Cells. *J. Fuel Cell Sci. Technol* 2012 9(2), 021014.

[6] Falcucci, G., Succi, S., Montessori, A. et al. Mapping reactive flow patterns in monolithic nanoporous catalysts. *Microfluid Nanofluid* 2016 20: 105. doi:10.1007/s10404-016-1767-5.

[7] Facci, A.L., Sánchez, D., Jannelli, E., Ubertini, S. "Trigenerative micro compressed air energy storage: Concept and thermodynamic assessment" Applied Energy 158, 243-254, 2015.

[8] Tommasi T., Salvador G., Quaglio M. New insights in Microbial Fuel Cells: novel solid phase anolyte. *Scientific Reports* 2016; 6 doi:10.1038/srep29091
[9] [2] Logan, B. E. Exoelectrogenic bacteria that power microbial fuel cells. *Nature reviews. Microbiology* 2009 7: 375–381.
[10] [3] Lovley, D. R. Bug juice: harvesting electricity with microorganisms. *Nature reviews. Microbiology* 2006 4: 497–508.
[11] Kiely, P. D., Regan, J. M. & Logan, B. E. The electric picnic: synergistic requirements for exoelectrogenic microbial communities. *Current opinion in biotechnology* 2011 22: 378–385.
[12] Karagiannidis A., Perkoulidis G. A multi-criteria ranking of different technologies for anaerobic digestion for energy recovery of organic fraction of municipal solid wastes. *Bioresource Technology* 2009 100: 2355-2360, DOI: 10.1016/j.biortech.2008.11.033
[13] Du Z., Li H., Gu T. A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy, *Biotechnology Advances* 2007 25: 464-482, DOI: 10.1016/j.biotechadv.2007.05.004
[14] Wang H.Y., Bernarda A., Huang C.Y., Lee D.J., Chang J.S. Micro-Sized microbial fuel cell: A mini-review. *Bioresource Technology* 2011 102: 235-243, DOI: 10.1016/j.biortech.2010.07.007
[15] Logan B.E., Hamelers B., Rozendal R., Schröder U., Keller J., Freguia S., Aelterman P., Verstraete W., Rabaey K. Microbial fuel cells: Methodology and technology. *Environmental Science & Technology* 2006 40: 5181-5192, DOI: 10.1021/es0605016
[16] Logan, B. E. & Rabaey, K. Conversion of Wastes into Bioelectricity and Chemicals by Using Microbial Electrochemical Technologies. *Science* 337, 686–690, 2012.
[17] Yates, M. D. Convergent development of anodic bacterial communities in microbial fuel cells. *The ISME journal*, 2012, 6.
[18] Rabaey K, Verstraete W. Microbial fuel cells: novel biotechnology for energy generation. *Trends Biotechnol.* 2005 23(6):291-8.
[19] Yunhee Lee, Nagamany Nirmalakhandan Electricity production in membrane-less microbial fuel cell fed with livestock organic solid waste. *Bioresour Technol.* 2011 102 (10): 5831-5. doi: 10.1016/j.biortech.2011.02.090.
[20] Pendyala B., Chaganti SR., Lalman JA., Heath DD. Optimizing the performance of microbial fuel cells fed a combination of different synthetic organic fractions in municipal solid waste. *Waste Manag*. 2016 49:73-82. doi: 10.1016/j.wasman.2015.12.032.
[21] Jia J, Tang Y, Liu B, Wu D, Ren N, Xing D. Electricity generation from food wastes and microbial community structure in microbial fuel cells. *Bioresour Technol.* 2013 144:94-99. doi: 10.1016/j.biortech.2013.06.072.
[22] Frattini D., Falcucci G., Minutillo M., Feronea C., Cioffi, Jannelli E. On the effect of different configurations in air cathode MFCs fed by composite food waste for energy harvesting *Chemical Engineering transactions* 49, 85-90, 2016., DOI: 10.3303/CET1649015.
[23] Jannelli E., Minutillo M., Cozzolino R., Falcucci G. Thermodynamic performance assessment of a small size CCHP (combined cooling heating and power) system with numerical models (combined cooling heating and power) system with numerical models. *Energy* 2014 65 (1): 240–249.
[24] Nastro R., Falcucci G., Minutillo M., Jannelli E. Microbial Fuel Cells in solid waste valorization: trends and applications, *Recent trends in solid and hazardous waste, Springer Nature Edition*, 2016.
[25] Nastro R.A., Dumontet S., Ulgiati S., Falcucci G., Vadursi M., Jannelli E., Minutillo M., Cozzolino R., Trifuoggi M., Erme G., De Santis E. Microbial Fuel Cells Fed by Solid Organic Waste: a Preliminar Experimental Study. Proceedings of the “European Fuel Cell Conference” EFC 2013 – Rome,11-13 December, pp.139-140. ISBN: 978-88-8286-297-8.
[26] Jannelli, N., Nastro, R.A., Cigolotti, V. Minutillo, M and Falcucci, G. Low pH, high salinity: too Too much for Microbial Fuel Cells? Applied Energy, Available online 3 August 2016, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2016.07.079.

[27] Falcucci, G., Bella, G., Chiatti, G., Chibbaro, S., Sbragaglia, M. and Succi, S. Lattice Boltzmann models with mid-range interactions, *Commun. Comput. Phys*. 2007 2: 1071-1084.
[28] Falcucci, G., Ubertini, S., Bella, G., De Maio, A. and Palpacelli, S. Lattice Boltzmann modeling of Diesel spray formation and break-up, *SAE Int. J. Fuels Lubr.* 2010 3(1):582-593.
[29] Montessori, A., Falcucci, G., Prestininzi, P., La Rocca, M. and Succi, S. Regularized lattice Bhatnagar-Gross-Krook model for two- and three-dimensional cavity flow simulations. Phys. Rev. E 2014 89(5), 053317.
[30] Krastev, V.K., Russo, S., Martini, F. and Falcucci, G. Direct Numerical Simulation of Flow Physics and Chemistry inside SCR Reactors, *SAE Tech. Paper* 2015-24-2507.
[31] Krastev, V.K., Falcucci, G., Jannelli, E., Minutillo, M. and Cozzolino, R. 3D CFD modeling and experimental characterization of HT PEM fuel cells at different anode gas compositions. *Int. J. Hydrogen Energ*. 2014 39(36): 21663-21672.

Biography

Giacomo Falcucci is Assistant Professor at the University of Roma “Tor Vergata”. He has been Visting Professor ar NYU Tandon School of Engineering and the School of Engineering and Applied Sciences of Harvard Universty. His research interests deal with Fluid Machinery, Energy Systems and Thermo-Fluid Dynamic Processes for Energy Conversion. He is author of more than 50 papers in first rank scientific Journals and has more than 500 citations.