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Molten carbonate fuel cell: An experimental analysis of a 1 kW system fed by landfill gas

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HIGHLIGHTS

- A novel cylindrical geometry 1 kW MCFC is analysed.
- A description of the considered experimental set-up is provided.
- The results of a suitable experimental campaign are discussed.
- The MCFC is fed by hydrogen, landfill gas and different mixtures of them.
- A comparative analysis of the so fuelled MCFC performance results is performed.

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ABSTRACT

In this paper the results of an on-site experimental analysis carried out on a Molten Carbonate Fuel Cell (MCFC) fed by different fuels (hydrogen, landfill gas and different mixtures of them) are presented. The examined MCFC is one of the experimental devices of an innovative power plant located at the urban landfill of Giugliano in Campania (Naples, Italy). Here, electricity is produced through four cogenerative reciprocating engines and one cogenerative gas turbine fed by landfill gas, operating since 2003. At the same site, two different fuel cells are installed for scientific purposes.

During the considered experimental campaign, the MCFC is initially supplied by hydrogen for testing the system at the best operating conditions. Afterward, the fuel cell is fed by mixtures of different ratios of hydrogen and reformed landfill gas. For this reason, the system is equipped with an external reformer and a suitable gas cleaning. In order to analyse the system energy performance under varying electricity loads (obtained through an electronic device), several tests were carried out. In addition, several stress tests were also performed aiming at analysing the system endurance when fed by landfill gas. The experimental results concerning the produced electric currents and voltages show satisfactory performance of the system, while the obtained operating temperatures and cell reliability still need to be improved.

1. Introduction

The most interesting advantages of Fuel Cells (FC) are flexibility of operation, low emissions and high conversion efficiency. The available FC technologies can be classified as a function of their operating features. Among them, high temperature fuel cells are presently the most attractive ones. Both Solid Oxide Fuel Cells (SOFC) [1,2] and Molten Carbonate Fuel Cells (MCFC) [3] belong to this category, since their operating temperatures range between 600 and 1000 °C [4]. High temperature fuel cells are especially attractive for their capability to use cheap and unconventional fuels (e.g. natural gas, methane, biogas, syngas, etc.), while other typologies of fuel cells require high-purity hydrogen as fuel.

In a MCFC, the electrolyte is an alkali carbonate or a combination of alkali carbonates and ceramic matrices of $LiAlO_2$ [4]. The high operating temperatures of MCFCs make them particularly suitable for stationary electricity and heat cogeneration [5]. A comprehensive review of MCFC systems for steady state use, in both grid and non-grid-connected applications (dispersed and distributed generation), with or without combined heat and power capability is presented in [6]. The operating temperatures of this technology reach about 650 °C, which is the temperature threshold required for ensuring the optimal electrolyte conductivity. An additional important advantage of this technology lies in the possibility to avoid the use of noble metals as catalysts during the oxi-

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Nomenclature

α	coefficient
β	coefficient
CH_4	methane
C_3H_6	cyclopropane
CO_2	carbon dioxide
$CO_3^=$	carbonate
$\Delta V/\Delta I$	ratio between the obtained voltage drop to the applied current (V/A)
H_2	hydrogen
HCl	hydrochloric acid
H_2O	water
H_2S	hydrogen sulphide
I	current (A)
MCFC	molten carbonate fuel cell
N_2	nitrogen
NH_3	ammonia
O_2	oxygen
P	MCFC electricity power (W)
SO_2	sulphur dioxide

Subscript

e	electron

dation and reduction processes. On the other hand, these high temperatures imply significant thermal stresses of several MCFC components and potentially reduce the durability of the whole system. Furthermore, when vaporization and corrosion of some metal components occur, the carbonate electrolyte may be lost from the of $LiAlO_2$ matrix determining a voltage decrease of the cell [7,8]. The MCFC concept is not new; it was originally developed in the Netherlands in 1950s. Subsequently, relevant research and development programs were developed in the United States in 1960s and Japan in the 1980s [9]. In the last years many improvements were accomplished aiming at improving the system efficiency and reliability.

Typically, MCFCs are fuelled by hydrogen, reformed methane or methanol. The possibility to feed the cells by renewable fuels enhances the environmental advantage of this technology and leads to sustainable system cycles. Biogas (with high methane concentration) is one of these fuels that show high potentials for decreasing the greenhouse gas emissions. Biogas is often utilized for generating electricity and heat through conventional combined heat and power (CHP) units [10,11], and it can be also exploited for feeding several typologies of FCs, such as SOFC and MCFC. The high content of CO (up to 40% [12]) included in the reformed gas (damaging for low temperature fuel cells) represents an improvement factor for feeding high temperature FCs [13]. In addition, both SOFC and MCFC are particularly tolerant to a number of components included in the biogas which would be as poisons for low-temperature fuel cells [4].

The high operating temperature of both SOFC (about 1000 °C) and MCFCs (about 650 °C) makes them particularly suitable for biogas exploitation [14,15]. The possibility to supply landfill gas to highly efficient energy conversion devices (MCFC and SOFC) attracted many researchers. Zappini et al. theoretically investigated the possibility to supply a MCFC and a reciprocating engine by landfill gas obtained by municipal waste. Their results showed a higher profitability of the reciprocating engine with respect to the one obtained by the MCFC system. This was essentially due to the high capital cost of the fuel cell and to the need of replacing the MCFC stack after 4 years of operation. Nevertheless, authors concluded that a possible MCFC cost reduction, due to a massive commercialization and economies of scale, would have changed the scenario in the next years [16]. Similar conclusions were achieved in several additional studies focused on the economic feasibility of these systems [17–20]. Obviously, the expected cost reduction may be achieved through a special effort made by academic institutions and manufacturers. In this regard, such topic was also dealt with in several other papers. As an example, in [21,22] a comparison among the performances of three different cogeneration systems (MCFCs, internal combustion engines and gas turbines) supplied by biogas produced through an anaerobic digestion plant (for wastewater, animal manure and organic solid waste) was carried out. Other economic and technical studies for high power output MCFCs (>300 kW) fed by biogas are reported in [20,23,24].

Similarly, a number of papers focused on different arrangements of SOFC power systems fed by biogas are available in literature. This idea was pioneered in the early 2000s when a number of researchers predicted the possibility to supply biogas or landfill gas to some SOFC systems [14]. The possibility to supply SOFC by landfill gas is also very attractive since it is theoretically possible to perform a carbon dioxide reforming avoiding the use of steam. This issue was addressed by Ni, performing parametric simulations showing that H_2O addition may decrease the performance of short SOFC at typical operating conditions as H_2O dilute the fuel concentration. However, H_2O addition is needed at reduced operating temperature, lower operating potential, or in SOFC with longer gas channel [25]. Wongchanapai et al. [26] recently investigated a combination of a direct-biogas SOFC with a micro gas turbine, focusing on the influence of the variation of several design parameters on the whole system performance. They concluded that the overall system efficiency can be improved by increasing pressure ratio, fuel utilization factor and gas turbine inlet temperature.

The majority of the papers available in literature only address this issue from theoretical and/or numerical points of view while very few works present experimental results obtained by supplying fuel cells by biogas and/or landfill gas. Santarelli et al. modelled and partially experimentally validated a tubular anode-supported solid oxide fuel cell (SOFC) fed by biogas from anaerobic digestion. They found out that the direct biogas utilization in an anode-supported SOFC is able to provide a good performance and to ensure an efficient conversion of the methane even when the cell temperature is far from its nominal value [27]. Experimental tests were also performed by using simulated mixtures of biogas by Calise et al. for a microtubular SOFC fuel cell. Authors found that the investigated cell was particularly sensitive to carbon deposition which significantly reduced the system performance [28]. For a similar experiment, Fuerte et al. found that cobalt doping of basic copper–ceria formulation enhanced sulphur and carbon coking tolerance of the SOFC anode material [29]. Staniforth and Kendall used a sample of landfill gas to show the feasibility to produce power by a SOFC. Results also showed problems in longevity. The final experiment produced a cell running at 18.5% efficiency for 5 h at a current density of 524 mA cm^{-2} [30]. A field test was also performed by a Finnish company showing the feasibility of using a 20 kW SOFC fed by landfill gas supplying electricity to 10 households. However, no relevant experimental data was published regarding this field test [31].

With respect to the studies based on the SOFC technology, very few papers, focused on the real operation of a MCFC fed by biogas,