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# Experimental Investigation on a Novel Electrolyte Configuration for Cylindrical Molten Carbonate Fuel Cells

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*An experimental investigation on a novel electrolyte configuration for molten carbonate fuel cells (MCFCs) is presented. A single cell facility was built. The cell is characterized by a cylindrical geometry in order to reduce the structural and thermodynamic problems which affect the lifetime of the traditional rectangular shape MCFCs. The main aim of this research is to evaluate the possibility of not installing the porous ceramic matrix in order to reduce the gas crossover problems of MCFCs and improve the cell lifetime. Thus, the new single cell was mainly constituted by the porous electrodes, the liquid electrolyte and structural disks as electrolytic support. Different solutions were studied as mechanical support for the electrolyte. Experimental tests on the proposed solutions were performed. Results suggested that the proposed adjustments are a promising solution for increasing the lifetime of cylindrical MCFCs and reducing their costs. [DOI: 10.1115/1.4003773]*

*Keywords: control, degradation, experimental results, geometry variations, MCFC*

## 1 Introduction

Molten carbonate fuel cells (MCFCs) are characterized by the following cost-effective theoretical properties that could lead to a future commercialization as stationary energy production plants [1,2]:

- high efficiency (theoretically up to 60%);
- low environmental impact;
- low fabrication costs of the industrialized product;
- cogeneration due to the high temperature working conditions;
- high tolerability to the fuel impurities;
- possibility to be directly supplied by natural gas from grid thank to internal or external reformer stages.

However, MCFCs are characterized by technical limits which slow their commercialization, especially for the residential market: long start-up times, a lifetime limited by gas crossover phenomena and stability of the materials (they may be affected by corrosion and oxidation phenomena). Currently, a mature technology is only limited to large size MCFCs (over 100 kW).

Traditional shape MCFCs are characterized by a square or rectangular geometry [1,2]. Novel cylindrical cell geometries for small size MCFCs were patented and proposed in previous works [3–6]. The cylindrical geometry of the cell components (electrodes, matrix) helps to reduce the traditional problems of square and rectangular geometry MCFCs. In fact, traditional MCFC elements are produced by the tape casting technique [7]; cylindrical cell elements may be easily obtained by injection moulding, a technique which may be conveniently used for large scale productions of small size cells, with high benefits in terms of fabrication times and costs. Furthermore, traditional MCFCs are characterized by high thermal outward dispersions. A cylindrical geometry helps to minimize the thermal dispersions both for its geometry intrinsic properties and the easiness to thermally insulate such device. This

property contributes to improve the cell global efficiency. Cylindrical MCFCs are also characterized by:

- reduced gas sealing problems due to the lack of edges;
- external manifolds which allow different stack size;
- a reduced compression strain disuniformity on each plate contact surface due to the symmetry of the cell elements.

A cylindrical small size MCFC is the result of multi-annual activities performed at the Fuel Cell Laboratory of University of Perugia headquartered in Terni (Italy); it is patented by IPASS [3–6]. The optimum size for the mentioned cylindrical MCFCs is in the [1 kW, 5 kW] range: in this way, the mentioned benefits, thermal self-sustain conditions, cogeneration and a compact design may be obtained. A previous work showed the proposed technology suitable for  $\mu$ CHP applications; a \$2000/kW target price was determined by an economical evaluation [8].

This paper reports the results of an experimental investigation on novel solutions for improving the performances of the mentioned cylindrical MCFCs by reducing the gas crossover phenomena due to the porosity variability of ceramic matrices. The proposal is to avoid the installation of the porous matrix as electrolyte support. Different structural solutions were tested by a specific single cell cylindrical facility. The single cell facility was mainly constituted by porous electrodes (anode and cathode), the liquid electrolyte and structural disks as electrolytic support. Experimental tests were conducted to determine the optimum configuration and to evaluate the suitability of the proposed solutions. Voltage-current density and power-current density characteristic curves were compared for each tested configuration in order to determine the best solution as electrolytic support. Results showed that the proposed MCFC configuration may be a viable solution to increase MCFC lifetime and to solve the gas crossover problems which have put back their commercialization for residential  $\mu$ CHP applications.

## 2 Gas Crossover on MCFCs: The Proposed Solutions

MCFC lifetime is particularly affected by gas crossover phenomena, which typically consists in anodic gas drift toward the cathodic compartment: in particular, two kinds of gas crossover phenomena may occur for MCFC traditional configurations: structural gas crossover and diffuse gas crossover through the porous matrix.

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Structural gas crossover is given by the cell configuration discontinuities. For example, anodic gases may go directly to the cathodic compartment through the cell edges or a gas manifold edge. A cylindrical MCFC configuration with vertical gas manifolds gives a great reduction of this kind of gas crossover phenomena: thermal dilatations are compensated from the cylindrical structure and its pressure seal mechanical system [4–6]. On the contrary, structural gas crossover phenomena often occur for the rectangular section traditional MCFCs with lateral gas manifolds [9].

Diffuse gas crossover through the porous matrix is given by the traditional  $\gamma$ -LiAlO<sub>2</sub> MCFC matrix characteristics. The matrix is installed between the electrodes (anode and cathode); in this way, it holds the Li/K molten carbonates between the two electrodes, avoiding their leakage through the other cell components. Furthermore, the matrix keeps the two electrodes separated: in this way, the electrode collapse is avoided and the anodic and cathodic compartments are electrically insulated. Thus, the matrix has to be characterized by specific chemical-physical characteristics in order to give the mentioned properties to the cell. However, some problems occur which affect the MCFC performances due to the difficulty to obtain optima matrix characteristics.

Firstly,  $\gamma$ -LiAlO<sub>2</sub> is not a common material; thus, its cost is very high and this fact increases the global cell cost.  $\gamma$ -LiAlO<sub>2</sub> ceramic matrices are installed into the cell in a “green” state (joined by an organic binder). The organic binder successively melts and evaporates during the cell conditioning step, which is a very long process (approximately 1 week); hence, conditioning and start-up processes are very sensitive phases because they may affect the matrix configuration and the stack working conditions. Furthermore, the matrix production is usually obtained by a humid molding technique, which is a very hard and long process. Thermal resistance and porosity specifications for the produced matrices are very strictly; thus, the production process may demand a drastic selection for the finished products and the costs may further increase. The produced matrices are also characterized by a very low resistance to the mechanical stresses: thus, problems may occur for their transport and the cell assembling process.

Hence, the need of installing a porous matrix makes the MCFC assembling process very hard: the role of the porous matrix is important for having correct MCFC working conditions, but it introduces many problems. As mentioned before, the matrix porosity is a fundamental parameter to have correct working conditions. Li/K molten carbonates distribution has to give a stable three-phase (gas-electrolyte-solid) interface. It may be obtained in MCFCs exclusively by a balance in capillary pressures. The diameters of the largest flooded pores are related by the following equation (1)

$$\frac{\gamma_a \cos \theta_a}{D_a} = \frac{\gamma_c \cos \theta_c}{D_c} = \frac{\gamma_m \cos \theta_m}{D_m} \quad (1)$$

where  $\gamma$  is the interfacial surface tension,  $\theta$  the contact angle of the electrolyte,  $D$  the pore diameter and subscripts  $a$ ,  $c$ , and  $m$  refer to the anode, cathode and electrolyte matrix, respectively. Typically, the porosity characteristics of these elements have to be the followings [1,10]:

- anode: 3–6  $\mu\text{m}$  average pore diameter, 45–70% porosity;
- cathode, 7–15  $\mu\text{m}$  average pore diameter, 70–80% porosity;
- matrix, average pore diameter < 1  $\mu\text{m}$ , 30–70% porosity.

Figure 1 shows a SEM analysis of a typical  $\gamma$ -LiAlO<sub>2</sub> matrix in which its porosity is evidenced. If the correct porosities are not obtained, cross-over phenomena may occur. In particular, a matrix with too large pores may induce a critical electrode flooding phenomenon, instability in the three-phase interface and gas crossover due to the osmosis processes. Micro-channels are created which connects anodic and cathodic compartments. Gas crossover induces the contact between hydrogen and oxygen: catalytic

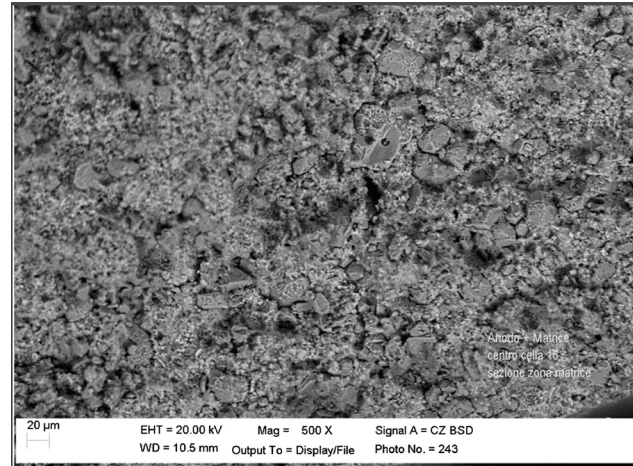


Fig. 1 SEM analysis of a typical MCFC matrix

combustion processes may occur because of the nickel content in anode and cathode. The result is a critical degradation of the MCFC structure and working conditions. This kind of gas crossover is a critical problem also for the cylindrical MCFC configuration above mentioned: in fact, it is given by the matrix presence and the problems in its production process.

Thus, a novel configuration for cylindrical MCFCs is here proposed in order to reduce the problems due to gas crossover through the porous ceramic matrix: the configuration is studied to avoid the installation of the  $\gamma$ -LiAlO<sub>2</sub> porous matrix. Furthermore, the problem to obtain a high uniformity of the molten carbonate distribution is solved by the proposed configuration without the  $\gamma$ -LiAlO<sub>2</sub> matrix. In fact, the liquid electrolyte is naturally uniformly distributed in its MCFC compartment.

However, other technical problems rise up. It is necessary a new method to preserve the osmosis balance for a correct three-phase interface; this problem may be solved by determining optima differential pressures between electrode and electrolyte compartments. These optima values have to be assured in order to reproduce the same cathode and anode flooding rate as in traditional porous matrices.

Another problem is to manage the loading, heating and melting phases of Li/K carbonates. Thus, new geometries, start-up procedures and specific electrolytic support materials more economic and commercially available than  $\gamma$ -LiAlO<sub>2</sub> were identified. Materials with high resistance to high temperatures (600–650 °C is the typical MCFC working temperature range) and pressures were tested as electrolytic supports: in particular, macor and phlogopite were studied. Tests were conducted by a specific single cell facility where the proposed arrangements were installed.

### 3 The Cylindrical Single Cell Facility

A single MCFC facility was built in order to test the proposed solutions for increasing the cylindrical MCFC lifetime. It is mainly constituted by a reactor made of the following components:

- (1) two steel plates which bound the anodic and cathodic compartments;
- (2) a nickel-oxide porous cylindrical cathode (1 mm thick, 90 mm diameter);
- (3) the electrolyte;
- (4) the electrolytic support disk;
- (5) a nickel-chrome porous cylindrical anode (1 mm thick, 90 mm diameter).

Figures 2, 3 and 4 shows the reactor scheme, a picture of the reactor and its internal assembling scheme, respectively. The reactor is characterized by a vertical configuration. The anodic compartment is on the bottom steel plate. The nickel-chrome porous anode

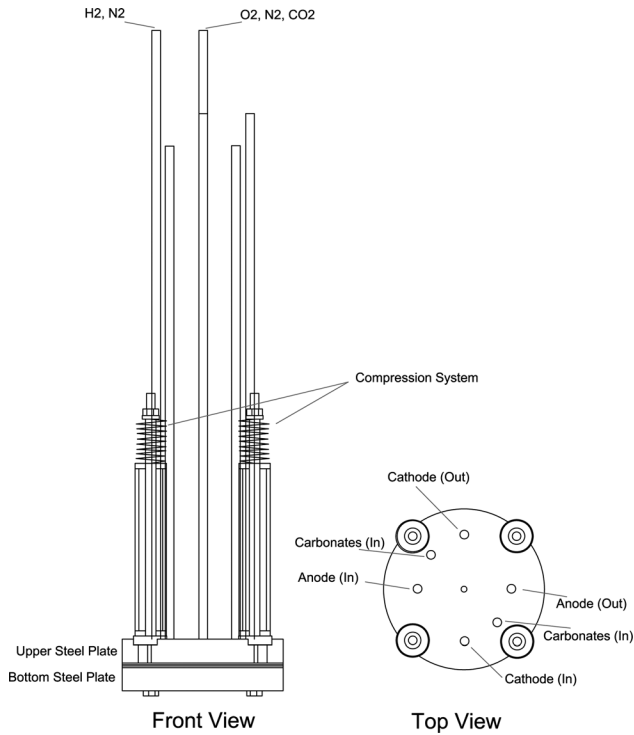


Fig. 2 The single cell reactor scheme



Fig. 3 A picture of the single cell reactor

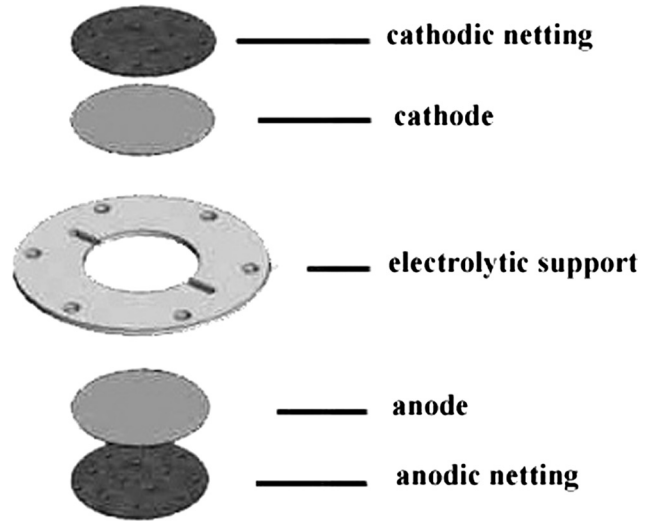


Fig. 4 The single cell reactor internal assembling scheme

is installed over this plate. The cathodic compartment is placed below the upper steel plate: the porous cathode is installed on this plate. Gas distribution is attained by stacking steel nettings between each electrode and the corresponding steel plate. Nettings have also the role of electrode support system [3–6]. Electrical current manifolds are connected to the electrode nettings. Gas supply and exhaust external manifolds are vertically connected to the upper steel plate. The anode, the electrolytic support and the cathode are holed in order to have the correct internal circulation of the anodic supplied and exhaust gases. The electrolytic support is placed between the two electrode compartments; it bounds the electrolytic compartment. Two kinds of electrolytic support materials were tested: macor and phlogopite. Their role is to avoid structural gas cross-over and electrical short-circuit phenomena. External ties are installed by a leaf spring system in order to obtain a uniformly distributed compression strain. The amount of Li/K carbonates was not chosen in order to optimize the cell electrochemical performances but to assure the cell working and a simple installation of the electrolytic support materials. In this way, the main purpose of the proposed investigation, that is to verify the suitability of the proposed electrolytic support materials, was obtained. However, the distance between the electrodes and the high thickness of the carbonate layer gives a high ohmic resistance with respect to the optima values [11]. Impedance measurements showed that the real part of the cell ohmic impedance is in the [25–40] mΩ range for all the phlogopite configurations, in the [150–190] mΩ range for the macor configuration; it may be reduced also by 15–20 times when the carbonate thickness and the distance between the electrodes will be optimized in a future facility which will be characterized by the tested configuration which gave the best results.

The MCFC facility was also constituted by auxiliary systems in order to control and measure the cell temperature, the gas flow rates and the differential pressures between the electrode and electrolytic compartments.

The system for MCFC heating is constituted by a band electrical resistor (15 mm height, 300 kW power). The resistor is installed on the lateral surfaces of the steel plates. It is made of a ceramic material with high electrical insulation properties: thus, cell short-circuit is avoided. The resistor is supplied by a digital control module based on the temperature measured by a thermocouple installed into the reactor. Alumina layers are also installed around the resistor-reactor system as thermal insulators.

The gas supply systems provides hydrogen and nitrogen to the cell anodic compartment (nitrogen has the role of gas diluent for the anodic compartment), air (oxygen and nitrogen) and carbon dioxide to the cell cathodic compartment. They are made by gas



Fig. 5 A picture of the entire single cell facility

bottles, mass-flow systems, manometers, electrovalves, and pressure reducers. Gas flow rates are controlled and monitored by data acquisition and digital control modules.

The proposed MCFC configuration may be characterized by carbonate dispersion problems which can affect the correct three-phase interface and the cell working conditions. Therefore, the correct electrode flooding rate obtained by the matrix porosity has to be kept also by the proposed configuration. A control system constituted by pipes, needle valves, ball valves, manometers and data acquisition/control modules was installed to control the differential pressures between each electrode compartment and the electrolytic one. Two manometers are used to measure the electrolytic compartment pressure. Two manometers are also used to measure the anodic and cathodic compartment pressures. Needle valves are connected to the exhaust ducts of each electrode compartment in order to control the pressure conditions. Ball valves are used to control the electrolytic compartment pressure relatively to the electrode compartment ones. Thus, the pressure control system may give a cell which works with the same electrode flooding rate of the cell with the porous matrix.

A variable electrical load was connected to the cell for evaluating its electrical performances and comparing the proposed configuration solutions. The single cell voltage and current were measured by Hall effect probes, inconnel wires and electrical multimeters.

A picture of the entire single cell facility is shown in Fig. 5.

#### 4 Experimental Tests

Experimental tests were conducted by the single cell facility to evaluate the suitability of the proposed solutions. Two electrolytic supports were tested: macor and phlogopite. They are materials with high electrical insulation properties (volume resistivity higher than  $10^{13} \Omega\text{-cm}$ ) and resistance to high working temperatures (their stability is assured up to 900–1000 °C). Furthermore, no corrosion or deterioration phenomena may occur when they are in contact with the electrolyte also for long term exposures: it was verified by the cylindrical MCFC equipped with the  $\gamma\text{-LiAlO}_2$  matrix where they are usually used as electrical insulation materials and they are in contact with the same electrolyte [3–6]: no corrosion or deterioration phenomena occurred both for macor and phlogopite, also for 10.000 h exposures to the electrolytic contact.

The performances of the proposed cylindrical MCFC configuration were evaluated by varying the following parameters:

- working temperature;
- gas flow rates;
- pressures in the anodic, cathodic and electrolytic compartments;
- kind of electrolytic support;

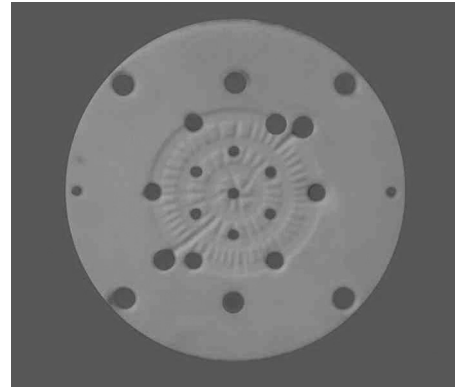


Fig. 6 A picture of the macor electrolytic support

- reaction active area of the electrodes.

Three kinds of experimental tests were performed: the first one was conducted by using macor as electrolytic support, the second and the third ones were conducted by using two configurations of phlogopite electrolytic support.

**4.1 Macor as Electrolytic Support.** Experimental tests were performed by using macor (a glass-ceramic material) as electrolytic support. The proposed electrolytic support is characterized by a 3 mm thickness and a 100 mm diameter. It has a 1 mm thickness and a 50 mm diameter groove where Li/K carbonates take place (see Fig. 6). Furthermore, holes and grooves are made on the support in order to maximize the reaction active area and uniformly distribute the Li/K carbonates into the electrolytic compartment. The obtained reaction active area for  $\text{CO}_3^-$  crossing is larger than  $3.04 \text{ cm}^2$ .

Experimental tests were conducted by the single cell facility in the mentioned configuration. Voltage- current density (V-J) and power-current density (W-J) characteristic curves were evaluated by varying the cell working temperature (see Figs. 7 and 8). Tests were performed by keeping constant the differential pressure between each electrode compartment and the electrolytic one. Also gas flow rates were constant during the tests, in order to determine the cell behavior toward temperature. Table 1 shows the values of the gas flow rates and differential pressures between the cell compartments, which were appropriately determined after preliminary tests. The highest pressure was kept at the anodic compartment in order to compensate the weight contribute of the Li/K carbonates on the electrode. The open-circuit voltage (OCV) versus temperature was also evaluated. Results show that OCV values are very close to the traditional MCFC ones: maximum

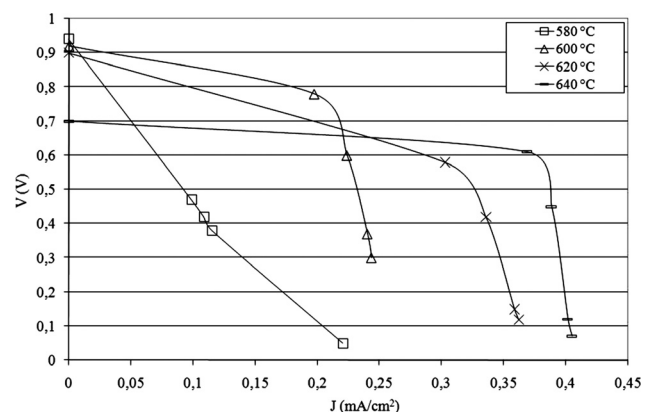


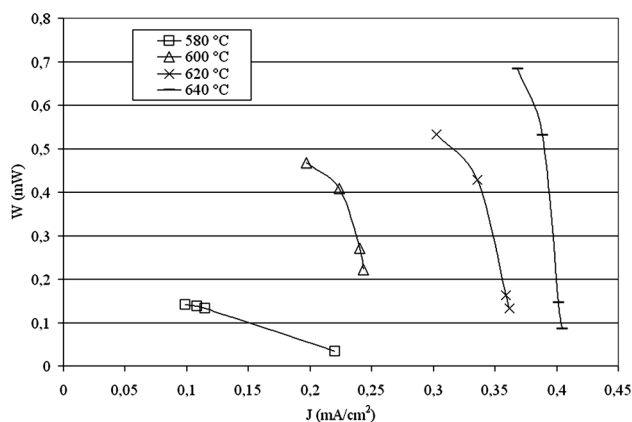
Fig. 7 Cell voltage- current density (V-J) characteristic curve for different working temperatures (macor electrolytic support)

**Table 1 Gas flow rates and differential pressures between the cell compartments (single cell with macor as electrolytic support and single cell with phlogopite as electrolytic support – (A) and (B) configurations)**

Working temperature (°C)	Anodic gases flow rate (10 <sup>-3</sup> m <sup>3</sup> /h)		Cathodic gases flow rate (10 <sup>-3</sup> m <sup>3</sup> /h)			Differential pressure (Pa)	
	H <sub>2</sub>	N <sub>2</sub>	CO <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	Anode versus Electrolyte	Cathode versus Electrolyte
Every working temperature	50	45	40	234	63	490.3	247.1

OCV is 0.98 V when temperature is 575 °C, but it is in the [0.7–1.0] V range for each working temperature. OCV values are also reported in Fig. 7. Thus, macor may be a good solution as electrical insulator between the electrode compartments. Otherwise, current values are very low (see Fig. 7). This is due to the too high support thickness which increases the ohmic polarization losses more than expected. In fact, maximum current intensity is 1.23 mA (when temperature is 640 °C), which corresponds to a 0.40 mA/cm<sup>2</sup> current density. Also maximum power is very low (0.68 mW); it also occurs when temperature is 640 °C (see Fig. 8).

Furthermore, other problems were shown after the tests. Li/K carbonates were inserted into the cell by pipes connected to the upper steel plate (see Fig. 2). During the final reactor disassembly, a carbonate solid block was found into the mentioned pipes. This fact may be due to the temperature gradient into the vertical pipes which avoided the Li/K carbonates to reach the electrolytic compartment; otherwise, it may be due to the higher pressure of the electrolytic compartment with respect to the external one which caused the carbonates to go back during their path into the mentioned pipes. No carbonate traces were found on the anodic and cathodic nettings. This fact and the low obtained current values



**Fig. 8 Cell power-current density (W-J) characteristic curve for different working temperatures (macor electrolytic support)**



**Fig. 9 Picture of the bottom steel plate of the reactor after its disassembly**

demonstrated the not complete electrolytic compartment filling by the carbonates.

Moreover, macor support was found to be cracked. It was probably occurred at the end of the 640 °C working temperature tests when a sudden voltage downfall was measured. This is also attested by Fig. 9 which shows the bottom steel plate of the reactor after its disassembly. The plate central part is characterized by a bluish color; thus, hydrogen combustion occurred into the reactor due to cross-over phenomena caused by the support cracking.

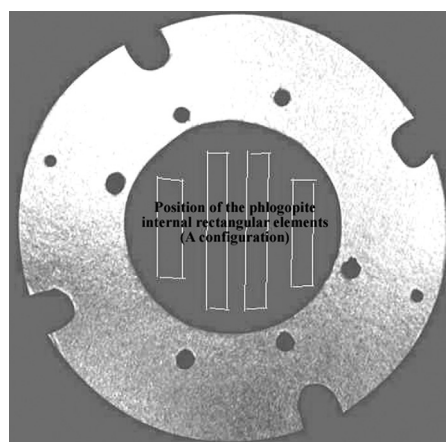
**4.2 Phlogopite as Electrolytic Support.** The problems reported in 4.1 Sec. suggested to replace the macor electrolytic support with another suitable material. Phlogopite was chosen: it is a material belonging to mica and silicate groups and is characterized by high thermal resistance (structural stability up to 1000 °C), high mechanical resistance, high electrical insulation properties (volume resistivity higher than 10<sup>13</sup> Ω-cm), working easiness and high availability [12].

Figure 10 shows the phlogopite support holed disk. It is characterized by 1 mm thickness; its shape gives a 19.62 cm<sup>2</sup> reaction active area.

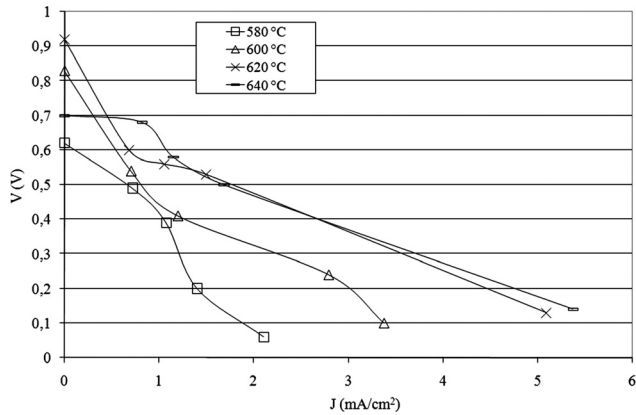
The lower support thickness and the greater reaction active area with respect to the macor configuration were chosen to improve the reactor performances. However, this configuration might increase the electrode collapse probability. Thus, two phlogopite support configurations were tested:

- (A) small phlogopite rectangular section elements were inserted into the electrolytic compartment (see their position in Fig. 10), in order to reduce the probability of electrode collapse. Their global area is 5.25 cm<sup>2</sup>. Thus, the reaction active area is reduced to 14.37 cm<sup>2</sup>.
- (B) the phlogopite disk shown in Figure 10 was used without the mentioned rectangular section elements (reaction active area is 19.62 cm<sup>2</sup>).

**4.2.1 Tests by (A) Configuration.** Preliminary tests were performed by the same carbonate insertion method of macor tests.



**Fig. 10 A picture of the phlogopite electrolytic support where the position of the internal rectangular elements ((A) configuration) is shown)**

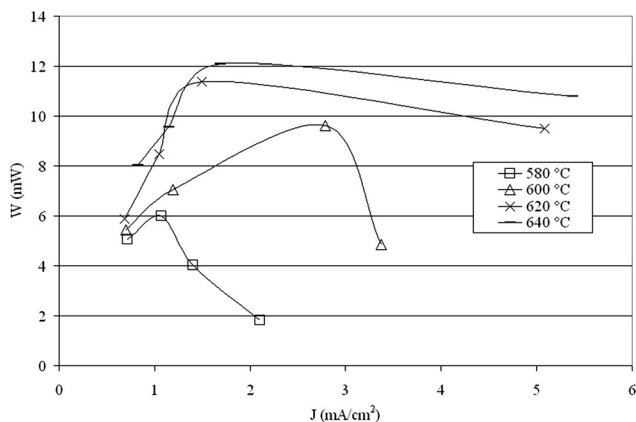


**Fig. 11 Cell voltage-current density (V-J) characteristic curve for different working temperatures (phlogopite electrolytic support, (A) configuration)**

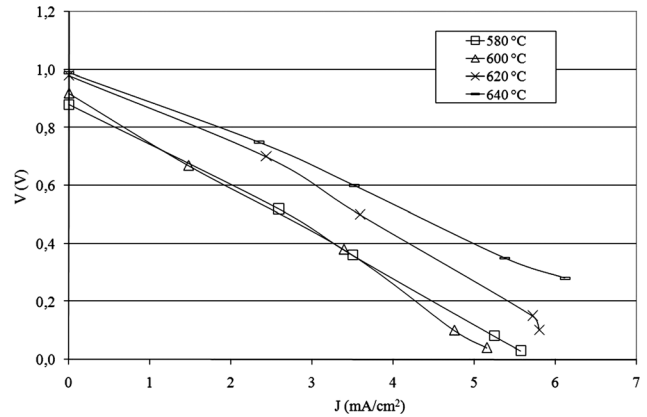
Better results were obtained in terms of cell performances but Li/K carbonates were found in their inlet pipes as in the macor tests. Thus, next tests were conducted by introducing Li/K carbonates into the electrolytic compartment during the cell assembly phase in order to avoid the not complete carbonate melting. Voltage-current density (V-J) and power-current density (W-J) characteristic curves obtained by (A) configuration (with carbonates introduced in the cell assembly phase) are shown in Figs. 11 and 12, respectively.

Table 1 shows the values of the gas flow rates and differential pressures between the cell compartments, which are the same of the macor tests.

Maximum current intensity is 77.20 mA (when temperature is 640 °C), which corresponds to a 5.37 mA/cm<sup>2</sup> current density. Maximum power is 12.10 mW and it also occurs when temperature is 640 °C. Furthermore, results show that cell performances in terms of current intensity and voltage values improve when temperature increases during the tests. About the differential pressure values, it was found that maximum current intensity occurred when the anode-electrolyte differential pressure was about 490 Pa for 640 °C temperature. Results show also that the maximum OCV is 0.92 V when temperature is 635 °C. Furthermore, a fuel flux rate increase jointly with a temperature growing was found to give an OCV improvement. OCV values are also shown in Fig. 11: they are averagely lower than the ones obtained by macor support. Thus, macor support is probably better as electrical insulation material than phlogopite. On the contrary, after the cell disassembly, no cracking phenomena were found on the cell



**Fig. 12 Cell power-current density (W-J) characteristic curve for different working temperatures (phlogopite electrolytic support, (A) configuration)**



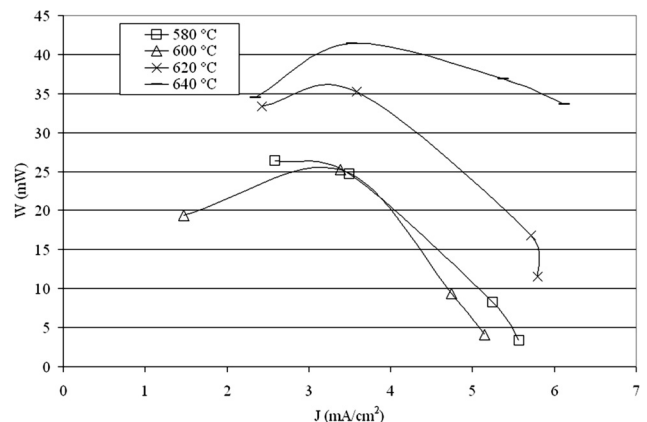
**Fig. 13 Cell voltage-current density (V-J) characteristic curve for different working temperatures (phlogopite electrolytic support, (B) configuration)**

components differently from macor tests. However, during OCV tests, while OCV values were growing toward temperature, a sudden voltage drop occurred at 610 °C. Electrode nettings were found flooded of carbonates, in particular the cathodic one; this is probably due to the phlogopite rectangular elements placed into the electrolytic compartment central area which caused the cathodic flooding overflow and the mentioned sudden voltage drop. Thus, phlogopite shows better mechanical performances than macor, but less electrical insulation performances. Furthermore, phlogopite rectangular elements caused a sudden drop of the cell performances; thus, they were removed for the next phlogopite tests (B) configuration.

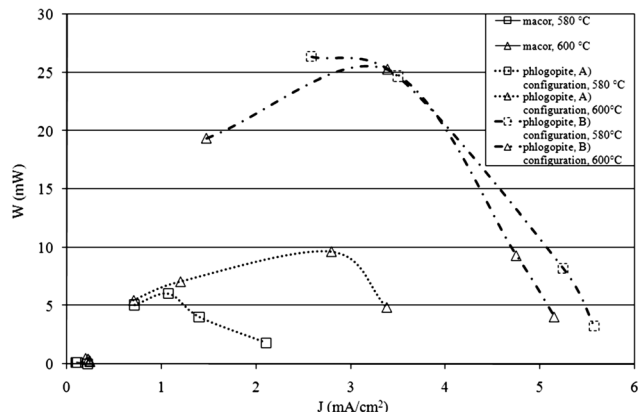
**4.2.2 Tests by (B) Configuration.** Tests by (B) configuration were conducted with the gas flow rates and differential pressures values shown in Table 1. Li/K carbonates were introduced into the electrolytic compartment during the cell assembly phase. Phlogopite rectangular section elements were not installed in the electrolytic compartment central area. This configuration is characterized by the following possible benefits:

- greater reaction active area (about 19.62 cm<sup>2</sup>);
- larger volume of carbonates inserted into the electrolytic compartment (about 1.96 cm<sup>3</sup> in the tested configuration);
- reliability of inserting the electrolyte in its compartment, avoiding problems of not complete carbonate melting.

Otherwise, this configuration is characterized by a higher probability of electrode collapse due to the absence of the electrolytic



**Fig. 14 Cell power-current density (W-J) characteristic curve for different working temperatures (phlogopite electrolytic support, (B) configuration)**

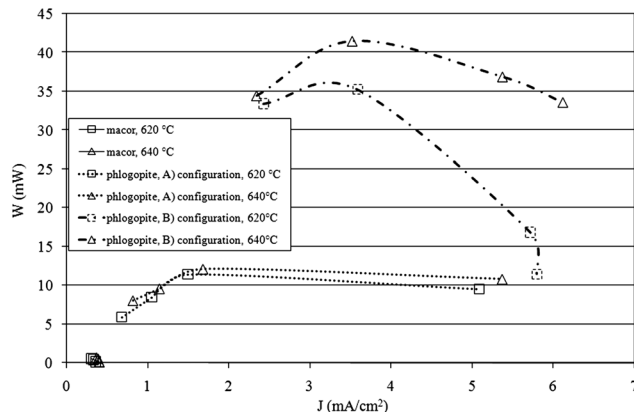


**Fig. 15 Comparison among the power-current density (W-J) characteristic curves of the tested configurations (580 °C and 600 °C working temperatures)**

support in the central area of the electrolytic compartment; a high electrode flooding rate may also occur.

Voltage-current density (V-J) and power-current density (W-J) characteristic curves obtained by (B) configuration are respectively shown in Figs. 13 and 14 (working parameters in Table 1). Also OCV values are shown in Fig. 13. It is shown that a temperature growing induces an improvement of the cell performances. Maximum current value is 120.05 mA at 640 °C which corresponds to a 6.12 mA/cm<sup>2</sup> current density. Maximum power is 41.45 mW at 640 °C. Furthermore, OCV values are very close to the traditional MCFC ones for each temperature condition. The maximum value (1.01 V) was obtained at 630 °C. Thus, results show the good gas sealing of electrode and electrolytic compartments.

The measured power and current densities values evidenced that phlogopite in (B) configuration (without the rectangular section elements in the electrolytic compartment central area) is the



**Fig. 16 Comparison among the power-current density (W-J) characteristic curves of the tested configurations (620 °C and 640 °C working temperatures)**

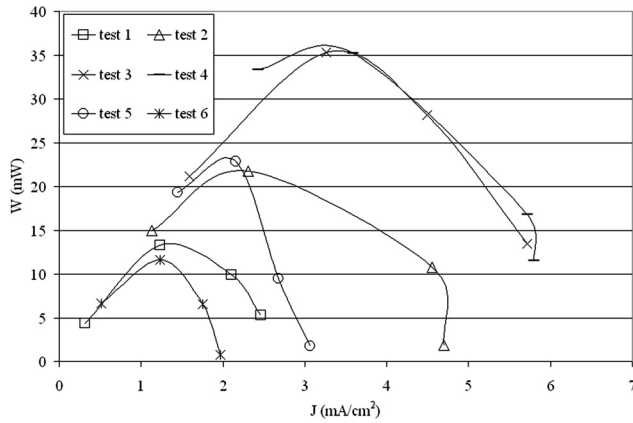
best candidate as electrolytic support for all the tested working temperatures. This is stated by Figs. 15 and 16 which show a comparison in terms of (W-J) characteristic curves among the three tested configurations.

Moreover, further tests were performed to evaluate the effect of differential pressures on the cell performances. In fact, the differential pressure between the electrode and the electrolytic compartments is a very important parameter to be controlled to determine high cell performances. Tests were conducted for the working temperatures which gave the best performances (620–640 °C) in the previous experiments. Differential pressures and gas flow rate values are reported in Table 2.

Power-current density (W-J) characteristic curves obtained by (B) configuration and the working parameters of Table 2 are reported in Figs. 17, 18, 19, and 20.

**Table 2 Gas flow rates and differential pressures between the cell compartments (single cell with phlogopite as electrolytic support – further tests by (B) configuration)**

Working temperature (°C)	Anodic gases flow rate (10 <sup>-3</sup> m <sup>3</sup> /h)		Cathodic gases flow rate (10 <sup>-3</sup> m <sup>3</sup> /h)			Differential pressure (Pa)	
	H <sub>2</sub>	N <sub>2</sub>	CO <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	Anode versus Electrolyte	Cathode versus Electrolyte
620 (test 1)	50	45	40	234	63	98.1	85.1
620 (test 2)	50	45	40	234	63	294.2	147.2
620 (test 3)	50	45	40	234	63	392.2	200.2
620 (test 4)	50	45	40	234	63	490.3	247.1
620 (test 5)	50	45	40	234	63	735.4	392.2
620 (test 6)	50	45	40	234	63	980.6	560.6
620 (test 7)	100	50	50	156	42	98.1	85.1
620 (test 8)	100	50	50	156	42	294.2	147.2
620 (test 9)	100	50	50	156	42	392.2	200.2
620 (test 10)	100	50	50	156	42	490.3	247.1
620 (test 11)	100	50	50	156	42	735.4	392.2
620 (test 12)	100	50	50	156	42	980.6	560.6
640 (test 1)	50	45	40	234	63	98.1	85.1
640 (test 2)	50	45	40	234	63	294.2	147.2
640 (test 3)	50	45	40	234	63	392.2	200.2
640 (test 4)	50	45	40	234	63	490.3	247.1
640 (test 5)	50	45	40	234	63	735.4	392.2
640 (test 6)	50	45	40	234	63	980.6	560.6
640 (test 7)	100	50	50	156	42	98.1	85.1
640 (test 8)	100	50	50	156	42	294.2	147.2
640 (test 9)	100	50	50	156	42	392.2	200.2
640 (test 10)	100	50	50	156	42	490.3	247.1
640 (test 11)	100	50	50	156	42	735.4	392.2
640 (test 12)	100	50	50	156	42	980.6	560.6



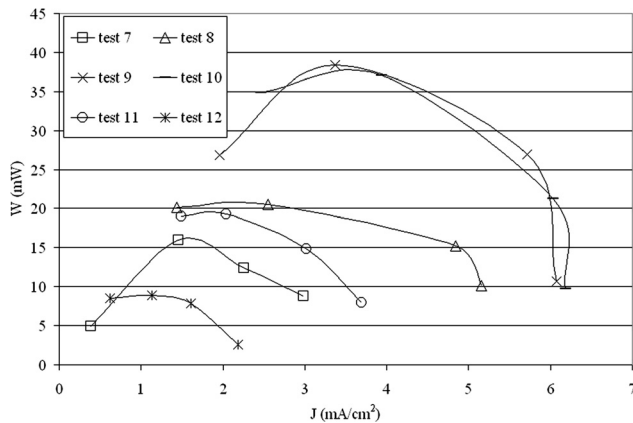
**Fig. 17 Cell power-current density (W-J) characteristic curve for 620 °C working temperature (phlogopite electrolytic support, (B) configuration, tests 1–6, see Table 2)**

Results shows that 640 °C is the working temperature which gave the best results in terms of produced power: 3.06 mW and 22.12 mW are, respectively, the average and the maximum difference between the produced power at 640 °C and 620 °C. The optimum differential pressure between anodic and electrolytic compartments is in the [350, 500] Pa range while the optimum differential pressure between cathodic and electrolytic compartments is in the [150, 250] Pa range (they correspond to tests 3, 4, 9, and 10).

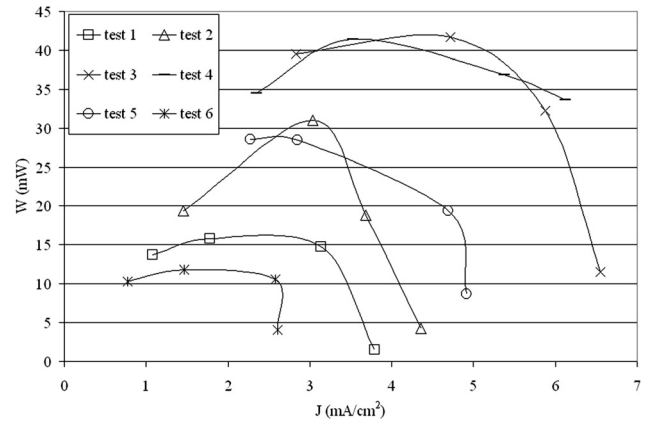
For constant differential pressures, better performances are obtained by increasing H<sub>2</sub> flow rate and reducing O<sub>2</sub> flow rate: 1.94 mW and 8.28 mW are respectively the average and the maximum difference between the produced power at 620 °C in (7–12) tests and in (1–6) tests; 3.36 mW and 15.92 mW are, respectively, the average and the maximum difference between the produced power at 640 °C in (7–12) tests and in (1–6) tests.

After these tests, the reactor was disassembled. It was shown that:

- the electrodes were flexed toward the electrolytic compartment;
- a cathode cracking occurred in radial direction;
- the phlogopite support was partially impregnated of carbonates in its inner zone.
- The deformation and cracking of the electrodes are due to the too high differential pressures applied in the last tests at 620 °C and 640 °C. In fact, tests were performed for growing differential pressures (see values of the differential pressures in Table 2).



**Fig. 18 Cell power-current density (W-J) characteristic curve for 620 °C working temperature (phlogopite electrolytic support, (B) configuration, tests 7–12, see Table 2)**



**Fig. 19 Cell power-current density (W-J) characteristic curve for 640 °C working temperature (phlogopite electrolytic support, (B) configuration, tests 1–6, see Table 2)**

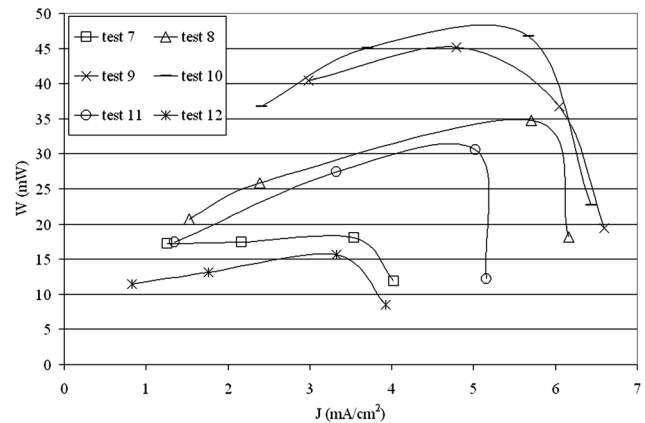
**4.3 Results and Comments.** The operative conditions for optimizing the performances of the proposed cell were identified by the proposed experimental tests. It was shown that the correct anodic and cathodic carbonate flooding rate may be reproduced by the differential pressure control on behalf of the porous matrix.

Results showed that better performances were obtained by the proposed solutions for working temperatures in the [620 °C, 640 °C] range. In fact, for the same gas flow rate and differential pressure conditions, the maximum produced power is:

- 0.68 mW at 640 °C, 0.53 mW at 620 °C, 0.46 mW at 600 °C, 0.14 mW at 580 °C for macor tests.
- 12.10 mW at 640 °C, 11.39 mW at 620 °C, 9.62 mW at 600 °C, 6.00 mW at 580 °C for (A) configuration phlogopite tests.
- 41.45 mW at 640 °C, 35.22 mW at 620 °C, 25.27 mW at 600 °C, 26.37 mW at 580 °C for (B) configuration phlogopite tests.

Thus, the best performances were obtained by using phlogopite as electrolytic support for the proposed MCFC configuration, in particular by (B) configuration.

Further tests by (B) configuration phlogopite and different gas flow rate and differential pressure conditions showed that better performances were obtained when the differential pressures between the electrode compartment and the electrolytic compartment were respectively in the [350, 500] Pa range (anode-electrolyte) and in the [150, 250] Pa range (cathode-electrolyte) for all the tested working temperatures. The average difference between



**Fig. 20 Cell power-current density (W-J) characteristic curve for 640 °C working temperature (phlogopite electrolytic support, (B) configuration, tests 7–12, see Table 2)**

the produced power at the optimized differential pressure conditions and the one at the other tested conditions is 11.63 mW and 18.36 mW, respectively, when the working temperature is 620 °C and 640 °C. For constant differential pressures, better performances are obtained by increasing H<sub>2</sub> flow rate and reducing O<sub>2</sub> flow rate: 8.28 mW and 15.92 mW are the maximum increase respectively obtained when the working temperature is 620 °C and 640 °C. However, oxygen (air) flow rate has to be slightly higher than the stoichiometric value to obtain better performances.

Some different problems were also found, such as deformations and cracking of the electrodes, particularly the cathode, when gauge pressures were too high (anode-electrolyte differential pressure over 800 Pa and cathode-electrolyte differential pressure over 400 Pa); thus, the control of gauge and differential pressures has to be very accurate. Furthermore, the electrolyte management in the working and power-off phases and the introduction of the carbonates in the cell are very sensitive phases.

Further tests are going on in order to solve the mentioned problems; they will also be useful to determine adjustments for identifying the optimum electrolyte layer thickness and increasing the cell performances in the best proposed configuration.

## 5 Conclusions

In this paper, a novel MCFC configuration which does not involve the porous matrix was investigated and tested by a cylindrical single cell facility. Electrolytic supports made by macor and phlogopite were proposed and tested: the aim was to give to the cell the same mechanical stability and electrical insulation properties of a traditional MCFC with lower fabrication costs. Differential pressures between the electrode and the electrolytic compartments were controlled by a specific system in order to have the same flooding rate of a traditional cylindrical MCFC [3–6]. Experimental results showed the suitability of the proposed solutions: in particular, more promising performances were obtained by the phlogopite support, thanks to its electrical insulation properties combined with its corrosion chemical resistance and its mechanical stability. The management of the liquid electrolyte, given by a specific system which controls the gauge pressure of each cell compartment, was optimized for the [620 °C, 640 °C] temperature range and for a differential pressure between the anodic compartment and the electrolytic compartment in the [350, 500] Pa range. Adjustments have just to be

found to limit electrode deformations or cracking phenomena (especially for the cathode). These are mainly due to the pressure control system which has to be very accurate also to reduce the electrode flooding rate. However, the good compatibility of the proposed electrolytic supports with the proposed configuration suggested to perform further experimental tests to reduce the mentioned problems: these tests are actually going on. Furthermore, the electrolyte layer thickness and the distance between the electrodes were chosen in order to assure the cell facility working and a simple installation of the electrolytic support materials. In this way, the main purpose of the proposed investigation, that is to verify the suitability of the tested electrolytic support materials, was obtained. However, the distance between the electrodes, the thickness of the carbonate layer and the cell configuration have to be optimized in order to increase the cell power production performances and evaluate the cell life performances, its suitability for  $\mu$ CHP fuel cell applications and its viability for industrialization processes: it will be the topic of future investigations which will be made after identifying a definitive solution as electrolytic support disk. Thus, the obtained results may be considered as the first step toward the development of the proposed novel MCFC typology.

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