Advances in Science and Technology Research Journal
Volume 10, No. 29, March 2016, pages 147–151
DOI: 10.12913/22998624/61946

Review Article

CAPTURING EXHAUST CO_2 GAS USING MOLTEN CARBONATE FUEL CELLS

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Received: 2015.12.15
Accepted: 2016.02.01
Published: 2016.03.01

ABSTRACT

Carbon dioxide is considered as one of the major contenders when the question of greenhouse effect arises. So for any industry or power plant it is of utmost importance to follow certain increasingly stringent environment protection rules and laws. So it is significant to keep eye on any possible methods to reduce carbon dioxide emissions in an efficient way. This paper reviews the available literature so as to try to provide an insight of the possibility of using Molten Carbonate Fuel Cells (MCFCs) as the carbon capturing and segregating devices and the various factors that affect the performance of MCFCs during the process of CO_2 capture.

Keywords: carbon dioxide capture, molten carbonate fuel cells, gas turbines.

INTRODUCTION

The ability of a special type of fuel cells called the Molten Carbonate Fuel Cells to work in the CO_2 rich environment through an electrochemical reaction in which CO_2 is transferred from the cathode side of the fuel cell to the anode side through the molten carbonate electrolyte in a form of carbonate CO_3^{2-} ions is the main reason of the possibility of its use as the CO_2 capture and segregation device. The main reactions occurring on the anode and cathode [1] are reported below along with the pictorial representation of the molten carbonate fuel cell presented in Figure 1. It is clearly visible how a molecule of CO_2 per reaction is transferred from cathode to anode side through carbonate ion (CO_3^{2-}):

Anode side $$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \quad (1)$$

Cathode side $$1/2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \quad (2)$$

Global reaction $$H_2 + 1/2O_2 + CO_{2(cat)} \rightarrow H_2O + CO_{2(an)} \quad (3)$$

MCFC AS CARBON DIOXIDE CAPTURE DEVICES

One of the most researched topic is the retro-fitting of MCFC stacks to the existing power plants and using the CO_2-rich exhaust of the power plants as the cathode gas of the molten carbonate fuel cell and fuel, normally hydrogen, is fed to the anode of the fuel cell. This is also termed as cogeneration, as the same fuel is used in the fuel cell to produce electricity using the heat from the exhaust of same power plant and at the same time CO_2 is also captured from the exhaust stream.

Figure 2 by U. Desideri et al. [1] depicts how the process of cogeneration works and how it permits the saving of primary energy.

Several plants based on this cogeneration model are in operation in Italy as described in the study by Desideri et al. [1]. In Figure 3, on the right, the distribution of CHP plants in Italy is shown, where the yellow points are the natural gas-fueled plants [1]. Figure 3 depicts, on the left, the CO_2 capture process that involves three phases after the mining of fossil fuel: the capture, that takes place close to the power plant; the transport, performed by pipelines; the storage, which could be realized in various sites such as saline aquifers, depleted oil and gas fields and oceans depth [1].

In another numerical modelling of a 400 kW MCFC-based CO_2 separation plant by U. Desideri et al. [1]. The target of 63% CO_2 removal efficien-

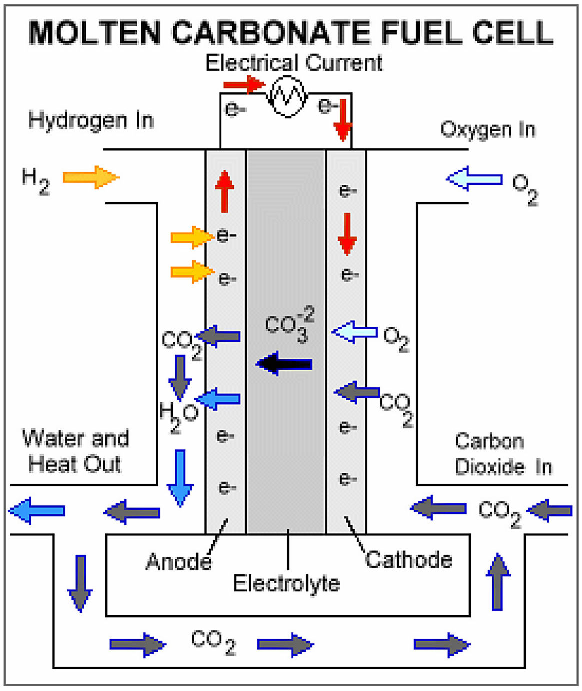

Fig. 1. The principle of operation of molten carbonate fuel cells (on the right) [1]

cy is achieved and the total efficiency in the right of 85% is achieved. These results are encouraging taking into account the fact that the system involving fuel cell technology is an active system as compared to other systems which need a lot of energy to operate [1].

A recent study by K. Sugiura et al. [4] elucidates the CO_2 removal characteristics of MCFC by performing experiments on a single cell MCFC with an electrode of area 81 cm^2. It is shown that the cathode CO_2 gas removal rate of 105 cc/min at approximately 175 mA/cm^2 can be achieved.

Figure 4 shows the CO_2 removal rate vs the current density achieved during the test [4]. The figure shows how the experimental values coincide perfectly with the theoretical values.

In another modelling study [2] by A. Amorelli et al. it was shown how a 1.6 MW MCFC reduced the CO_2 concentration from the exhaust of a 4.6 MW gas turbine by about 50% on per kW basis. Further review revealed that the CO_2 levels were decreased from 4.7%wt to 2.3%wt, that is about

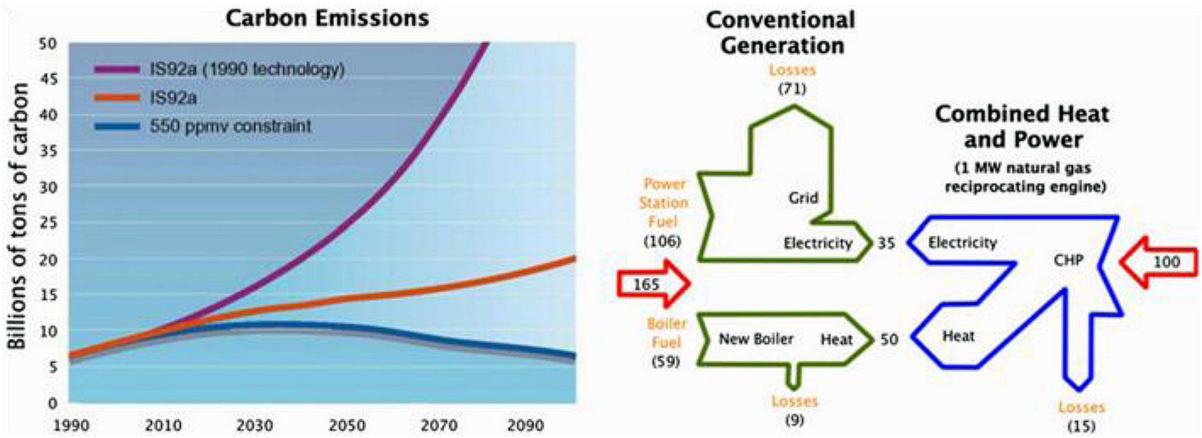

Fig. 2. Carbon dioxide emissions trend (left) and cogeneration vs. conventional generation comparison (right) [1]

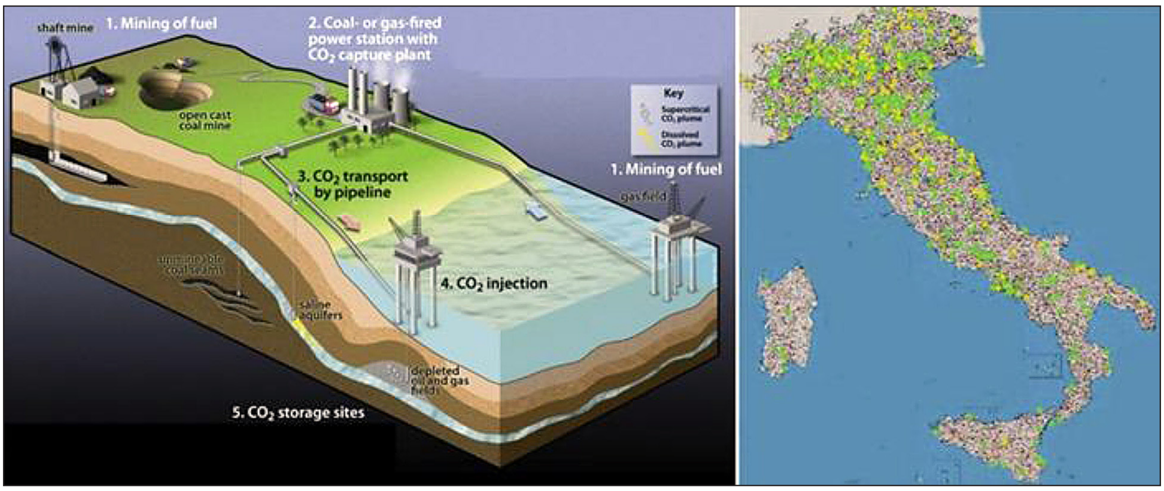

Fig. 3. CCS process (left) and small cogeneration plants diffusion in Italy (right) [1]

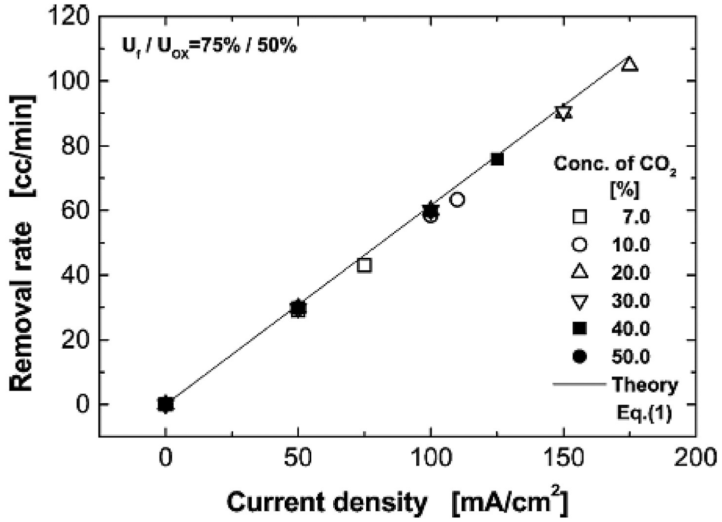

Fig. 4. CO_2 removal rate [4]

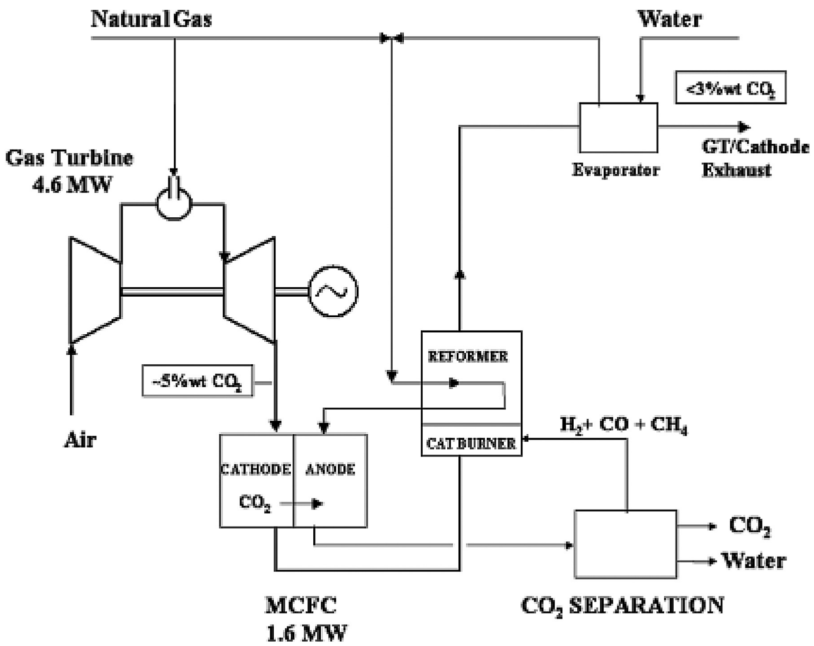

Fig. 5. Atmospheric pressure MCFC-gas turbine hybrid arrangement for CO_2 capture [2]

50% decrease across the fuel cell (i.e. from 3.2 tons per hour to 2.0 tons per hour, equivalent to a reduction of circa 10,500 tons per annum in case of the power plant model shown in Figure 5 below). The main idea of such a hybrid power plant [2] is depicted in the picture below.

It is clearly mentioned how the turbine exhaust contains approx. 5% wt. CO_2 and the cathode exhaust contains <3% wt. CO_2.

Another simulation by M. Lusardi et al. [5] involves a numerical model of a gas turbine rated at 4.6 MW, similar to the study by A. Amorelli et al. [2] with the treatable exhaust of about 2430 kmol/hr fed to a suitable fuel cell rated at 2 MW operating at 1atm and 3 atm is done.

In the study [5] it was shown that when the fuel cell is operated at 1 atm, 27.6 kmol/h of CO_2, which would otherwise be discharged into the atmosphere, can be captured which amounts to almost 37% reduction. When operated at 3 atm, almost 35.3 kmol/h of CO_2 is captured amounting to almost 63% removal.

EFFECT OF CATHODIC CO_2 CONCENTRATION ON MCFC PERFORMANCE

The concentration of CO_2 in the exhaust stream of the various power plants is considerably different thus the effects of the CO_2 concentration at MCFC cathode on the performance of the MCFC are also studied and reviewed. In a study [2] experiments were also performed on a single cell fuel cell at varying cathodic CO_2 concentration and the corresponding results are extrapolated to the larger scale plants. Single-celled fuel cell performance at various cathodic CO_2 concentrations is shown in Figure 6.

It is clearly visible that the optimal condition for the fuel cell performance is >7% vol CO_2 in the exhaust. According to the study [2] the performance of the fuel cell fell to approximately 690 W/m^2 at about 4% vol CO_2, which is typical of circa 1.47 MW MCFC system. The results show the feasibility of the usage of MCFC as CO_2 capturing devices even with the gas turbine power plants.

Other similar tests [3] incorporating a 125 kW rated MCFC stack and CO_2 content at the cathode as low as 3.9% has been performed and the current density of about 1200 A/m^2 with CO_2 utilization of 55.7% at maximum current has been obtained [3]. The results of the test [3] are shown in Figure 7.

CONCLUSIONS

The ability to capture carbon dioxide by molten carbonate fuel cells has been reviewed. This method of carbon dioxide capturing from the exhaust of the existing power plants provides promising results due to the fact that the use of fuel cells increases the overall efficiency of the power plant as described in the study by U. Desideri et al. [1]. The fuel cell carbon dioxide capturing systems have an inherent advantage over the conventional separation units because they produce electric power along with

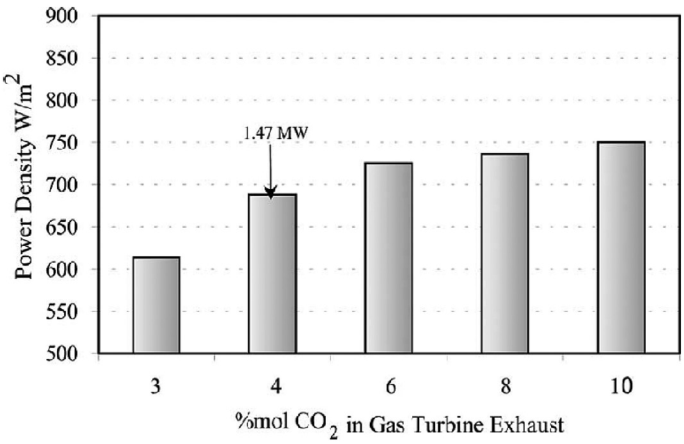

Fig. 6. Single cell experimental results [2]

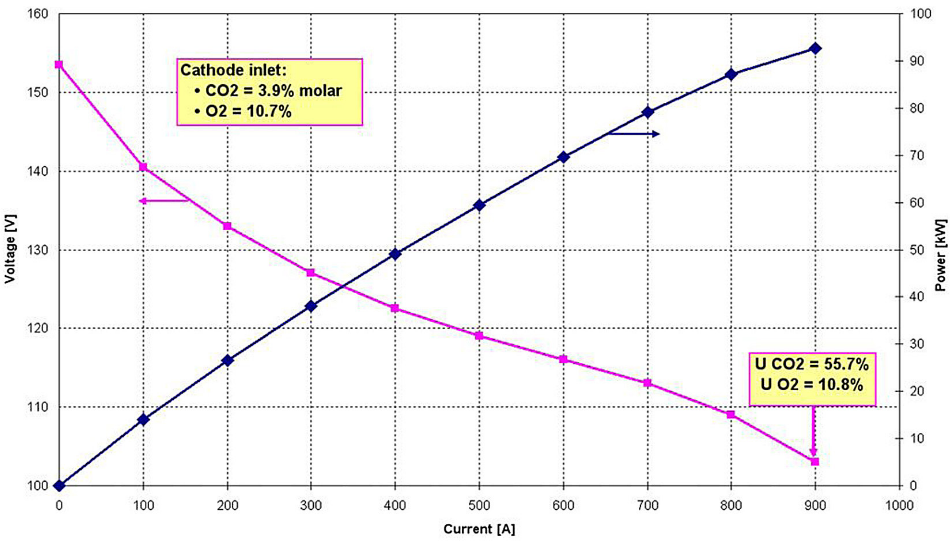

Fig. 7. Performance of a full-scale MCFC stack with a CO_2 content 3.9% molar at the cathode inlet [3]

the capturing of the emissions from the exhaust streams. Moreover, it can be seen that low concentration of CO_2 in the exhaust streams pose a challenge to the optimal performance of the MCFCs and this is also an active topic of research to enable the Molten Carbonate fuel cells to work efficiently at sub-optimal concentrations of CO_2 at fuel cell cathode as discussed in the studies by L. Caprile et al. [3] and A. Amorelli et al. [2]. In some studies the methods are also discussed to increase the performance of the fuel cells at lower CO_2 concentrations such as increasing the partial pressure of CO_2 as in the study by K. Sugiura et al. [4].

The results from the studies demonstrate an encouraging scenario in which MCFCs can be used effectively in hybrid arrangements with the power plants, particularly those based on oil and gas [2].

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