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Modeling and characterization of molten carbonate fuel cell for electricity generation and carbon dioxide capture

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Abstract

The growing electricity request and more severe commitments on emissions led to the research of more and more efficient energy transformation processes. The use of Fuel Cell in order to improve energetic and exergetic efficiency is well-assessed and a number of advanced processes and highly functional materials are currently under investigation, advising a high potential of these systems for the future development of sustainable energy technologies. In particular, the capabilities of integrating high temperature fuel cells within energy conversion systems having medium and high grade thermal sources (flue gases) has resulted in a renewed interest in Molten Carbonate Fuel Cells (MCFC). In fact, they operate at temperatures in the range of 600-700°C and they could be fed by unreformed gas, internally integrating a methane-steam reforming section (direct or indirect).
In this paper, the Authors present a theoretical activity finalized to the design and characterization of the integration of a MCFC in a coal fired power plant: a physical model of the fuel cell has been developed, where the energy and chemical processes are represented for the cell stack and geometrical and electrical parameters have been taken into consideration. The model has been applied for system analysis with respect to multiple steady states, sensitivity and stability behavior. Both direct and indirect internal reforming cases have been compared each other, evaluating the energetic and environmental performances of the use of the MCFC as CO_2 remover.

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Keywords: MCFC, CO_2 capture, repowering, steam power plants, modeling

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1. Introduction

Fuel cells are high efficiency electricity-generating systems that convert chemical energy from oxidation of the fuel directly into electric energy. They have been widely researched and developed as a promising clean and high-efficiency energy-generating technology in several sectors: electrical energy production is surely the most important one, but also in transportation sector the interest in fuel cell powertrains is raising, in particular for marine [1] and automotive applications [2][3].

Molten carbonate fuel cells (MCFCs) are high-temperature fuel cells that operate in the range of 600-700 °C [4],[5]. The MCFC has different advantages with respect to other fuel cell systems: it offers high fuel conversion efficiency and can operate with alternative fuels and hydrocarbons [6][7], so widening the potential application: molten carbonates are very stable systems under a wide range of chemical conditions and temperature ranges, giving the possibility of designing ideal reactions and electrolyte media for advanced chemical/electrochemical processes related to production, storage, conversion and efficient energy performance [8].

MCFCs have two types of fuel processing. One is an external reforming MCFC (MCFC-ER) that produces hydrogen at the outside of the MCFC stack. In this case, the stack temperature can be controlled by convection heat transfer only. Therefore, the external reforming adopts a pressurized operation to supply a high rate of cooling gas flow. The other type is an internal reforming MCFC that directly generates hydrogen in the MCFC stack. The stack temperature is controlled within the stack to remove the heat generated from the endothermic reforming reactions. Because the MCFC with internal reforming does not require a high flow rate, this fuel cell can operate under atmospheric conditions [9]. Internal reforming processes can be further divided in direct (MCFC-DIR) and indirect (MCFC-IIR) one: in the first case, the reforming is made in the anode room itself, with benefit on thermal exchange efficiency, on the other hand, the internal reforming, can be also made just adjacent the anode. The two types can be also integrated in a two-step reforming of the anode inlet flow [10].

The application of Molten Carbonate Fuel Cell (MCFC) technology to CO_2 capture and separation from flue gases represents one of the most interesting technology [11],[12]. In fact, the electrochemical reactions that take place within the MCFC involve the migration of the CO_2 from the cathode to the anode. During this process, the MCFC can operate as power generator and, simultaneously, as CO_2 separator from an exhaust gaseous stream (produced by a combustion process) and sent to the cathode [13][14]. This opens the way to a wide applicability of MCFCs (and also other high temperature fuel cells, like SOFC [15],[16]) as CO_2 remover and energy conversion in thermoelectric power plants. In fact, they can be fed by the exhaust gases of a gas turbine power plant [17][19] or integrated in a gas-steamcombined cycle power plant [20],[21].

In this paper, a physical model for the design of a MCFC is presented, considering both direct and indirect internal reforming. The model has been applied on the integration of a MCFC with a coal fired power plant [22]. The integration is realized using the MCFC as active unit for the CO_2 removal and a novel thermal recovery section has been introduced, using the residual heat, after the steam production needed for methane reforming, to partially preheat the feedwater in high- and low-pressure regenerative lines of the SPP. MCFC has been sized in order to capture the CO_2 from flue gases of the thermoelectric power plant and performances of the integrated system have been investigated. Great environmental and energetic improvements are achieved in terms of plant efficiencies and specific primary consumption for CO_2 avoided (SPECCA index).

Nomenclature

an	anode	*IIR*	Indirect Internal Reforming	*ref*	reference
ASU	Air Separation Unit	*in*	inlet	*SOFC*	Solid Oxide Fuel Cell
cat	cathode	*IPP*	Integrated Power Plant	*SPECCA*	Specific Primary Energy Consumption for CO_2 Avoided
comp	compression	*LHV*	Lower Heating Value		
DIR	Direct Internal Reforming	*M*	Molar mass	*SPP*	Steam Power Plant
ER	External Reforming ṁ	*ṁ*	mass flow rate	*U*	Utilization factor
F	Faraday constant	*MCFC*	Molten Carbonate Fuel Cell	*y*	molar fraction
h	enthalpy	*P*	Power	η	efficiency
HX	Heat Exchanger	*out*	outlet	φ	CO_2 removal factor
I	Current	*Q*	heat flux		