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Using MCFC for high efficiency CO_2 capture from natural gas combined cycles: Comparison of internal and external reforming

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HIGHLIGHTS

- We model the use of MCFC as CO_2 separator integrated in natural gas combined cycles.
- Internal reforming (IR) and external reforming (ER) configurations are considered.
- Oxycombustion of anode exhaust or cryogenic CO_2 capture are investigated.
- Most efficient is the IR-cryo with <1% penalty towards the basic combined cycle.
- Specific energy consumption for CO2 avoided limited to 0.4 MJ/kg_{CO2}.

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ABSTRACT

In recent years, several research groups have proposed the combination of Molten Carbonate Fuel Cells (MCFCs) and gas turbine cycles for the application to CO_2 capture. One of the most promising configuration relies on the use of MCFCs as "active CO_2 concentrator" in combined cycles (CCs): the fuel cell is placed downstream the gas turbine and ahead the heat recovery steam generator (HRSG), to concentrate the CO_2 from the gas turbine exhaust feeding the cathode, to the anode (where CO_2 is transferred together with oxygen) and generate electricity; while exhaust heat released by the cell effluents is recovered by the steam cycle. It has been shown that such plant configuration can capture 70–85% of CO_2 with small efficiency penalties compared to the combined cycle, and increasing by about 20% the overall power output (mainly given by the MCFC section); hence, this configuration could have relevant advantages with respect to competitive carbon capture technologies.

This work presents a comprehensive discussion of the results of a modeling activity developed at Politecnico di Milano regarding the possible use of MCFCs for high efficiency CO_2 capture from combined cycles. The work discusses different types of MCFC–CC cycles, focusing on the comparison of two families of MCFC and corresponding power plants which have been discussed only separately in the past. The MCFC can be fed with natural gas according to an internal reforming (IR) or external reforming (ER) process, according to the technological proposals of different MCFC manufacturers. Then, the anode exhaust stream of the MCFC, where is concentrated the majority of CO_2, is sent to a CO_2 purification section which can be based on (i) a cryogenic CO_2 separation section, or (ii) an oxy-combustion of residual fuel components, followed by cooling, condensation of water and separation of CO_2. In both cases, a high purity CO_2 stream is obtained and pumped to liquid form for storage.

Detailed results are presented in terms of energy and mass balances of the different proposed cycles, evidencing pros and cons of the different layout and pointing out the role of relevant FC operating parameters (CO_2 utilization, operating current density and voltage) on the overall balances. Moreover, it is presented a comparison between the best proposed cycles and conventional NGCC–CCS systems.

1. Introduction

It is well known that reduction of greenhouse gas emissions, including CO_2 emitted from power generation, is considered a crucial challenge for a sustainable development of our society. Among different CO_2 reduction approaches, Carbon Capture and Storage

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Nomenclature

ASU	air separation unit
ATR	auto-thermal reforming reactor
FC	fuel cell
CCS	carbon capture and storage
GT	gas turbine
HRSG	heat recovery steam generator
i_c	current density (mA/cm^2)
LHV	lower heating value (kJ/kg)
MEA	mono-ethanol ammine
MCFC	molten carbonate fuel cell
NG	natural gas
NGCC	natural gas combined cycle
SPECCA	specific primary energy consumption for CO_2 avoided (Eq. (7))
U_F	fuel utilization factor
U_{CO2}	CO_2 utilization factor
U_{O2}	O_2 utilization factor
V	voltage (V)
WGS	water Gas Shift

(CCS) can reduce by at least an order of magnitude the CO_2 emissions from fossil fueled power plants [1,2]. Although a debate exist about the necessity of this option with respect to other possible solutions for CO_2 mitigation, like heavily increasing the role of renewables [3], it is generally considered that CCS will play a relevant role in future energy scenarios [4].

Some reports [5,6] indicate that actual cost of CO_2 avoided for power plant with CO_2 capture can be competitive or even lower than some renewable power technologies (i.e. off-shore wind turbine, concentrated solar power and photovoltaic systems).

One of the most promising CCS strategies relies on post-combustion capture technologies, more easily applicable to existing power plants without requiring – with respect to other capture approaches – the development of specific turbomachinery and completely new power plant concepts.

Generally speaking, the application of post-combustion capture to conventional NGCC requires the adoption of chemical processes using solvents (amines, ammonia) to absorb CO_2 from the plant exhaust gases (where CO_2 concentration is typically limited to about 4%) before it is released into the environment [2]. CO_2 removal can approach 90%, at the price of a relevant decay in efficiency (about 8% points) and power output of the plant due to the considerable heat duty required to regenerate the solvent [4,7–9].

By contrast, in the power plant configurations discussed in this work, CO_2 separation is obtained using fuel cells. The concept of using fuel cells within large scale power cycles for CO_2 capture has been widely discussed in the last years, although most of the attention has been given to Solid Oxide Fuel Cells (SOFCs) [10,11]. They generally operate with an approach which is similar to the 'oxy-fuel' concept, oxidizing fuel with oxygen extracted from air while generating power, and releasing concentrated effluents at the anode outlet. This concept is shown on top of Fig. 1, where the anode exhaust is sent to a CO_2 separation train (based on chemical or physical separation techniques [2]). This kind of power cycles generally require an integration with custom-tailored gas turbine cycles, often operating at unconventional turbine inlet temperatures and pressure ratios, either using natural gas as a fuel or coal through Integrated Gasification Fuel Cell (IGFC) concepts. Since most fuel is oxidized in the fuel cell to allow a high CO_2 capture efficiency, the FC generates the majority of the cycle power output [10–12]. The alternative option offered by Molten Carbonate Fuel Cells (MCFCs) is shown below in Fig. 1, where the fuel cell can operate "draining" CO_2 from the cathode inlet stream, receiving the flue gases of a conventional power plant. In this way the fuel cell operates with a post-combustion approach, although also oxidizing a minor portion of additional fuel with the same 'oxy-fuel' features discussed above. In the solution discussed in this work the gas turbine flue gases of a NGCC feed the cathode of a MCFC, which acts as an "active CO_2 concentrator" transferring carbon dioxide from the cathode to anode side, while generating power at very high efficiency.

Differently from other types of fuel cells (including SOFCs), MCFCs have already shown a promising progress towards industrialization, evidencing an encouraging deployment in terms of cumulated power output, reaching over 200 MW, and cost reduction [13–15].

The concept of using MCFCs as an "active" CO_2 capture component has already been introduced in previous works [11,16] and discussed with different plant layout and different fuel cell technologies [17,18]. MCFC models generally considered internal reforming and performances were calibrated towards literature data [19–21]. Results of these first investigations were promising, showing potential CO_2 capture when applied to NGCC of about 80% and efficiency penalty in the range of 1 to 2% points. Moreover, the plant net power output increases by over 20% thanks to the contribute of the MCFC section, and the power cycle layout does not change significantly with respect to a standard NGCC, making even possible to consider retrofit solutions.

This paper sets a final comparison of the different plant arrangements separately investigated in previous studies [17,18,22], presenting a comprehensive discussion of different possible fuel cell arrangement and plant layout, including also external reforming fuel cell configurations, based on a common set of assumptions. The work also discusses the comparison between the results of the proposed solution with those of conventional NGCC–CCS plants.

Results include detailed energy and material balances of the most promising cycle configurations; they confirm the relevant potential of the MCFC–CC concept in terms of high efficiency and low energy consumption for CO_2 avoidance, giving a potentially relevant advantage with respect to competitive carbon capture technologies.

2. Plant layout

All the power cycles proposed in this paper are based on a natural gas combined cycle (NGCC), where a MCFC is placed between the gas turbine and the heat recovery steam generator (HRSG). The gas turbine exhaust gases are directly used as cathode feed for the MCFC, where CO_2 is moved from the cathode to anode side, concentrating the CO_2 in the anode exhaust gases. This paper compares four MCFC–CC plant configurations deriving from the combination of two reforming arrangements and two CO_2 separation techniques.

In particular, the fuel cell section can be arranged according to:

- internal reforming (IR), meaning that the MCFC is fed at the anode side with mixture of natural gas and steam performing an internal reforming process;