



Energetic analysis of a syngas-fueled chemical-looping combustion combined cycle with integration of carbon dioxide sequestration



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ABSTRACT

Chemical-looping combustion for power generation has significant advantages over conventional combustion. Mainly, it allows an integration of CO₂ capture in the power plant without energy penalty; secondly, a less exergy destruction in the combustion chemical transformation is achieved, leading to a greater overall thermal efficiency. Most efforts have been devoted to systems based on methane as a fuel, although other systems for alternative fuels have can be proposed. This paper focus on the study of the energetic performance of this concept of combustion in a gas turbine combined cycle when synthesis gas is used as fuel. After optimization of some thermodynamic parameters of the cycle, the power plant performance is evaluated under diverse working conditions and compared to a conventional gas turbine system. Energy savings related with CO₂ capture and storage have been quantified. The overall efficiency increase is found to be significant, reaching values of around 5% (even more in some cases). In order to analyze the influence of syngas composition on the results, different H₂-content fuels are considered. In a context of real urgency to reduce green house gas emissions, this work is intended to contribute to the conceptual development of highly efficient alternative power generation systems.

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1. Introduction

Since fossil fuels are widely used for power generation, the effort required to achieve a real reduction of greenhouse gas emissions is enormous. However, it is possible to attain a short and medium term substantial reduction through sequestration of the CO₂ produced in fuels oxidation. The CCS (carbon capture and storage) could thus facilitate the transition to the use of new sources of clean energy.

There are basically three ways to preform CO₂ capture in practice: a) “post-combustion” capture via amine chemical absorption, e.g. described by Ref. [1]; b) “pre-combustion” capture, in the case of a previous fuel decarbonization to a mixture of H₂ and CO₂ takes place (several methods are assessed by Ref. [2]); c) “oxy-combustion”, in which the fuel is burned into oxygen instead of into air, and then nearly pure CO₂ is obtained after condensation of water.

The first to strategies, pre- and post-combustion capture, involve a high energy penalty, since they are based on conventional separation methods such as separation by membrane, chemical absorption or adsorption, and cryogenic separation. When pre-

combustion is possible, as in IGCC (integrated gasification combined cycles), it is energetically cheaper due to the fact that CO₂ is less diluted in the fuel than it is in the flue gases; but energy consumption is still significant. In the case of oxy-combustion, although energy savings strategies have been recently proposed to minimize the impact [3], the energy penalty occurs in the air separation unit rather than in the separation of CO₂.

The alternative technique of CLC (chemical-looping combustion) was first proposed by Ref. [4], and afterwards several researchers have contributed to the development of this technology. Nevertheless, most efforts regarding CLC applied to gas turbine systems have been dedicated to the study of methane as fuel, although alternative fuels such as methanol have been proposed as well [5]. This work focuses on the analysis of the energetic efficiency of a CLC gas turbine system fueled by synthesis gas (syngas hereinafter), in the base of a comparison with a similar gas turbine system with conventional combustion. There is also prior work on energetic analysis of a CLC gas turbine system with syngas as fuel [6,7] but in both cases only the gas turbine cycle is analyzed instead of a combined gas–steam cycle power plant, and the energy savings in the capture of CO₂ are not quantified. In this paper the overall energetic performance of a CLC combined cycled power plant fueled by syngas and with integrated CO₂ capture is analyzed in detail.

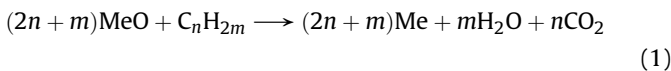
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Nomenclature		s°	standard entropy at 1 bar, (kJ/(mol·K))
c_p	constant pressure specific heat, (J/(mol·K))	<i>Subscripts</i>	
c_p°	zero-pressure specific heat, (J/(mol·K))	0, 1, 2, ..., 22	state numbers in the CLC cycle
CR	conversion ratio, dimensionless	0', 1', 2', ..., 7'	state numbers in a standard Brayton cycle
e	flow exergy, (kJ/mol)	298	standard thermochemical function evaluated a 25 °C (298.15 K)
h	specific enthalpy, (kJ/mol)	em	electromechanical energetic efficiency
LHV	fuel's lower heating value, (kJ/mol)	j	generic chemical component
K_a	equilibrium constant, dimensionless	c	thermodynamic properties at critical point
n	molar flow rate, (mol/s)	CC	combined cycle
p	pressure, (bar)	CC + CCS	combined cycle with carbon capture and storage
R	ideal gas constant, (J/(mol·K))	CCS	carbon capture and storage
s	specific entropy, (J/(mol·K))	CLC	working pressure of CLC reactors
T	temperature, (K)	CO ₂ C1, CO ₂ C2	CO ₂ compressors
v	specific volume, (m ³ /mol)	GT	gas turbine in a conventional Brayton cycle
W	power, (kW)	GT1, GT2	gas turbines in the CLC cycle
x	molar fraction, dimensionless	r	reduced temperature and pressure
z	compressibility factor, dimensionless	red	thermodynamic conditions at reduction reactor (fuel reactor)
<i>Symbols</i>		SC	simple cycle
η	thermal efficiency/energetic efficiency, dimensionless	ST	steam cycle
$\Delta\eta$	difference CLC – conventional thermal efficiencies, dimensionless	T	standard thermochemical function evaluated at temperature T
ζ	exergetic efficiency of steam cycle, dimensionless	<i>Superscripts</i>	
ω	acentric factor, dimensionless	(0), (1)	compressibility factor terms in Lee–Kesler equation
ΔG°	standard Gibb's function of reaction at 1 bar, (kJ/mol)	eq	at chemical equilibrium conditions
ΔH°	standard enthalpy of reaction at 1 bar, (kJ/mol)	in	initial conditions
$\Delta_f H^\circ$	standard enthalpy of formation at 1 bar, (kJ/mol)	M	mixing thermodynamic function

2. The chemical-looping combustion concept

The idea of the CLC system is illustrated in Fig. 1. The gaseous fuel is introduced into the reduction reactor and put in contact with an oxygen carrier, typically a metal oxide. We denote it generically by “MeO”. The fuel is then oxidized and the metal oxide is reduced, reacting in accordance with both:



Thus, the output stream from reduction reactor contains a gaseous mixture of CO₂ and H₂O, so that the only non-condensable gas in that flow is CO₂. The reduced metal oxide “Me” is then transferred to the oxidation reactor where it is oxidized in presence of air in accordance with:

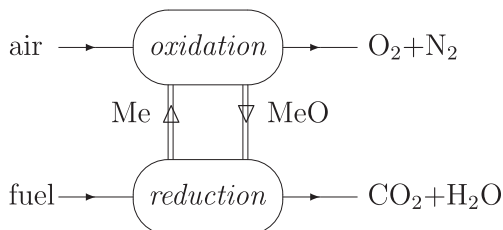


Fig. 1. Schematic diagram of the CLC concept.

As a result, at the outlet of this reactor oxygen-depleted air is obtained, i.e. basically N₂ and O₂ in a certain proportion.

Depending on both, fuel and oxygen carrier, the reduction reactions (1), (2) can be endothermic or exothermic, while the oxidation reaction (3) is always exothermic. If one or both of the reduction reactions is/are endothermic and they take place at low/medium temperature, then it would be possible to supply the needed heat from a medium temperature source, e.g. the exhaust gases in a gas turbine. If this is the case, since, according to Hess' Law, the overall amount of heat released in reduction and oxidation reactions must be equal to the fuel's heat of combustion, the oxidation reaction must have a heat of reaction higher than the conventional combustion. As a result, more heat is released at high temperature in comparison with a conventional combustion. CLC acts as a “chemical heat pump” transforming energy with a lower exergy content into energy with a higher exergy content. In other words, the overall exergy destruction due to irreversibility is lower with CLC than with conventional combustion. A very interesting recent theoretical analysis of this kind of “chemical energy amplification” can be found in Ref. [8].

On the other hand, the major advantage of CLC lies on the fact that the carbon dioxide that results from the fuel oxidation is not diluted with air or any other non-condensable gas, but contrarily it is obtained in a relatively pure form. This removes the need to invest energy for separation. The previous two aspects are the basis for this work. Furthermore, it can also be mentioned that in the CLC combustion process, the fuel and air pass through different reactors without flame, what provides an opportunity to minimize NO_x formation [9].

The CLC scheme in Fig. 1 can be implemented in practice in different ways, depending on the oxide's physical characteristics, the type of reactor and the operating conditions [10]. Typically fluidized-bed reactors are used, in which the metal oxides “float” as fine

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