



A comparative simulation study of power generation plants involving chemical looping combustion systems



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ABSTRACT

This work presents a simulation study on both energy and economics of power generation plants with inherent CO₂ capture based on chemical looping combustion technologies. Combustion systems considered include a conventional chemical looping system and two extended three-reactor alternatives (exCLC and CLC3) for simultaneous hydrogen production. The power generation cycles include a combined cycle with steam injected gas turbines, a humid air turbine cycle and a simple steam cycle. Two oxygen carriers are considered in our study, iron and nickel. We further analyze the effect of the pressure reaction and the turbine inlet temperature on the plant efficiency. Results show that plant efficiencies as high as 54% are achieved by the chemical looping based systems with competitive costs. That value is well above the efficiency of 46% obtained by a conventional natural gas combined cycle system under the same conditions and simulation assumptions.

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1. Introduction

It has been well documented that electric power plants using fossil fuels produce more than one third of the global carbon emissions (see Fig. 1; USEPA, 2015). As a result, there is a growing research interest in developing approaches for CO₂ mitigation from power generation. These approaches include (i) the use of renewable energy sources, (ii) the use of low-carbon fuels such as natural gas, (iii) the improvement of plant efficiencies and (iv) the capture of CO₂ from the energy systems.

A conventional process for CO₂ capture through amine absorption in a natural gas power plant based on current state of the art technologies reduces the thermal efficiency by about 10% (Brandvoll and Bolland, 2004). The challenge is then to generate alternative processes for CO₂ mitigation with a smaller penalty in efficiency.

The implementation of chemical looping combustion (CLC) systems emerged as one of the most promising techniques for CO₂ capture in power plants; CLC has the potential to separate CO₂ with only small penalties in plant efficiency. In the conventional version

of a CLC (see Fig. 2), combustion takes place into two separate reactors (oxidation and reduction reactors), using a metal that acts as an oxygen carrier; then, separate streams of exhaust air and CO₂ are obtained. Therefore, the oxygen carrier avoids direct contact of fuel and combustion air, and the CO₂ is then inherently separated from nitrogen; no additional process operations are needed for CO₂ separation.

State of the art technologies for natural gas fired combined cycles (NGCC) without CO₂ capture achieve plant efficiencies from 55–60%. Following the report by Brandvoll and Bolland (2004), and assuming a penalty of 10% due to CO₂ capture and compression, NGCC technologies can still reach an efficiency of 45–50%. As a result, to compete with current commercially available technologies, a CLC based power generation plant has to achieve net low heating value (LHV) plant efficiencies of 50% or higher.

This work presents a simulation study that provides a comparison among several configurations including the incorporation of CLC systems into various state-of-the-art technologies for power generation. The comparison also includes a conventional NGCC system. Two basic criteria are used for comparison: The net LHV plant efficiency and an economic assessment including the estimation of the capital investment, and operation and unit production costs. Additional results include the models sensitivity to the pressure in the reactors, the oxygen carrier and the gas turbine inlet

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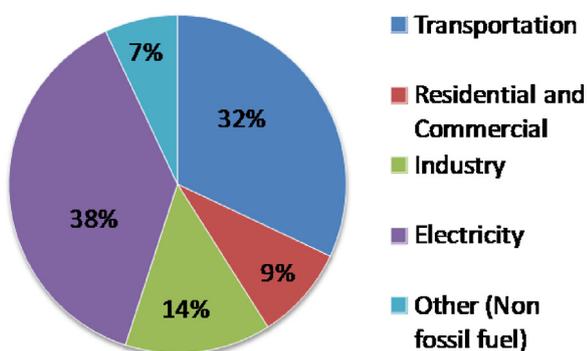


Fig. 1. 2013 global CO₂ emissions from fossil fuels (USEPA, 2015).

temperature (TIT). Then, this paper reports our results with respect to the technical and economic feasibility of CLC based power generation plants.

2. Background

The literature on CLC systems is extensive. Current research in CLC configurations focuses on the practical implementation of the various components of the system. Several studies have reported advances on novel extended CLC configurations and related simulation studies about their performance in power plants and other combustion processes.

2.1. Fundamentals of CLC and novel extended systems

The fundamentals of the chemical looping concept and its several reactor configurations have been extensively addressed. Some of the classical literature includes the works by (Ishida and Jin, 1996, 1997, 2001) and Jin and Ishida (2000). Those works provide the basic foundations of CLC and its potential application to gas turbine power generation cycles. Further developments consider the use of alternative fuels for the chemical looping combustor (Jin and Ishida, 2004). In fact, a coal-direct chemical looping (CDCL) process has been recently patented. Such a system converts pulverized coal feedstock to fuel in one integrated system without additional gasification, and allows both electricity and/or hydrogen production (Kim et al., 2013; Connell et al., 2013; Adanez et al., 2014).

The chemical looping concept has been extended to consider reforming (Chemical Looping Reforming, CLR), where complete oxidation of the fuel is prevented by using low air to fuel ratio (Ryden et al., 2006). Further, the simple CLC configuration has been extended to include a third reactor that favors the simultaneous generation of hydrogen. In this work we consider two instances of

those extended CLC configurations: The exCLC system described by Wolf and Yan (2005) and the CLC3 system proposed by Chiesa et al. (2008). Those configurations will be discussed in detail in Section 3 of this work.

2.2. Simulation and performance in power generation systems

Similar to our work, several authors have performed simulation studies and sensitivity analysis of various parameters, fuels, oxygen carriers, CLC configurations and power plant cycles. Most of the works include estimation of the net LHV plant efficiency. Among these works, Wolf and Yan (2005) studied a combined cycle and a steam injected gas turbine cycle (STIG) with both simple CLC and extended CLC (exCLC) configurations, finding efficiencies as high as 52%. Brandvoll and Bolland (2004) and Olaleye and Wang (2014) considered CLC-Humid Air Turbine (HAT) configurations reaching higher efficiency values (56%). Consonni et al. (2006) presented a comprehensive parametric analysis of CLC-combined cycle configuration using natural gas as fuel and iron as oxygen carrier. Gupta et al. (2006) focused their analysis in the CLR system, achieving hydrogen conversions as high as 82%. Jordal and Gunnarsson (2011) propose process configurations for handling unconverted fuel remaining in the captured CO₂-rich stream of a CLC system. Finally, recent developments report novel configurations which combine chemical looping combustion, the calcium-looping process, hydrogen production and the integrated gasification combined cycle for power generation (Fan and Zhu, 2015; Zhu and Fan, 2015; Zhu et al., 2015); simulation studies report the technical feasibility and economic potential of such combined/integrated systems.

2.3. Contribution of this comparative simulation study

Our study includes a conventional chemical looping (CLC) and its extended version (exCLC) for simultaneous hydrogen production, as well as the three-reactor configuration known as the CLC3 system. The power generation cycles used for our analysis include a combined cycle with steam injected gas turbines, a humid air turbine cycle and a simple steam cycle (SC). For the purpose of comparison, a conventional natural gas combined cycle (NGCC) was also simulated. We analyze the operation, investment and unit production costs as well as the net plant efficiency, and study the effect of the pressure on the system reaction and the material flows that control the turbine inlet temperature (TIT). To the best of our knowledge, there is not a single work which compares and analyzes the various configurations resulting from the use of the three CLC systems and the three power plant configurations studied in this paper. Therefore, we believe our paper contributes to the existing literature on the topic. In particular, results about the CLC3 system are quite limited.

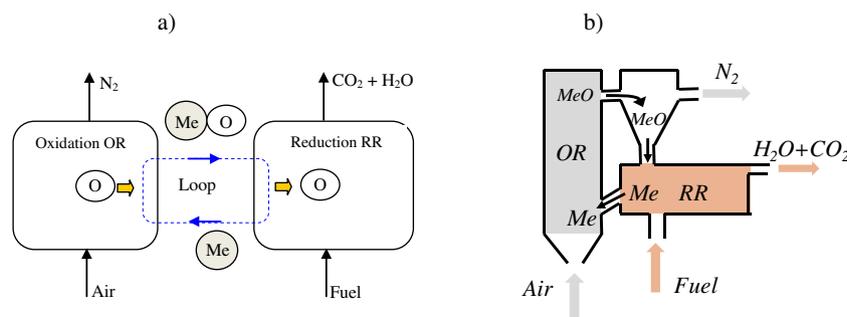


Fig. 2. Chemical looping combustion configuration. (a) The concept. (b) The system.

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