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Techno-economic analysis of chemical looping combustion with humid air turbine power cycle

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HIGHLIGHTS

- Process simulation for chemical looping combustion (CLC) and its model validation.
- Process simulation of humid air turbine (HAT) for power generation.
- Process simulation and analysis of CLC–HAT cycle.
- Economic analysis of the CLC–HAT cycle for natural gas-fired power plant with CO_2 capture.
- Comparison between CLC–HAT cycle and conventional HAT cycle.

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ABSTRACT

Power generation from fossil fuel-fired power plant is the largest single source of CO_2 emission. CO_2 emission contributes to climate change. On the other hand, renewable energy is hindered by complex constraints in dealing with large scale application and high price. Power generation from fossil fuels with CO_2 capture is therefore necessary to meet the increasing energy demand, and reduce the emission of CO_2. This paper presents a process simulation and economic analysis of the chemical looping combustion (CLC) integrated with humid air turbine (HAT) cycle for natural gas-fired power plant with CO_2 capture. The study shows that the CLC–HAT including CO_2 capture has a thermal efficiency of 57% at oxidizing temperature of 1200 °C and reducer inlet temperature of 530 °C. The economic evaluation shows that the 50 MW_{th} plant with a projected lifetime of 30 years will have a payback period of 7 years and 6 years for conventional HAT and CLC–HAT cycles respectively. The analysis indicates that CLC–HAT process has a high potential to be commercialised.

1. Introduction

1.1. Background

Fossil fuels are burned in power plants in a variety of ways. The combustion of fossil fuels produces flue gas stream (i.e. NO*x*, CO_2, SO*x*, CO, CH_4, and water vapour, etc.) with a CO_2 content of up to 14 vol% [1]. CO_2 is the largest and most important anthropogenic greenhouse gas (GHG) [2]. However, fossil fuel fired power plants play a key role in meeting energy demands. With growing concerns over the increasing atmospheric concentration of anthropogenic greenhouse gases, effective CO_2 emission abatement strategies are required to combat this trend [3]. In a fossil fuel-based power plant, CO_2 management is made up of three steps namely CO_2 capture (including separation and compression); transportation and storage [4]. There are three approaches for capturing CO_2 from use of fossil fuels and/or biomass for heat and power generation: pre-combustion, post-combustion and oxy-fuel process [5]. CLC is a relatively new CO_2 capture mechanism. The fuel is converted by its reaction with oxygen from an oxygen carrier rather than air (as in oxy-fuel and pre-combustion). CLC also enables the production of a concentrated CO_2 stream without the need for an expensive air separation unit [6]. The inherent CO_2 separation without severe energy penalties in the CLC process has drawn increased attention in light of power plant efficiency improvement and global warming potential due to fossil fuel combustion [4].

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Nomenclature

NCV	net calorific value (J/kg)
P	power output (MW)
NPV	net present value (£)
IRR	internal rate of return (%)
η_{ref}	efficiency of Conventional HAT cycle (%)
η_{ccs}	efficiency of HAT cycle with carbon capture (%)
W_{comp}	compressor work (MW)
Q	energy (MW)

Greek symbols

γ	yield
η	efficiency

Subscripts

comp	compressor
ccs	carbon capture and storage
ref	reference
GT	gas turbine
th	thermal

Acronyms

ASU	air separation unit
CFB	circulating fluidized bed
CLC	chemical looping combustion
CLC–HAT	chemical looping combustion with humid air turbine cycle
HAT	humid air turbine
PI	profitability index

1.2. Chemical looping combustion (CLC)

1.2.1. CLC concept

CLC is a method characterised by indirect fuel combustion because the air and fuel are never in direct contact. CLC differs from the oxy-fuel combustion strategy because of the concept of oxygen separation from air and the direct contact of pure oxygen and fuel in the latter [4]. In oxy-fuel combustion, the operation of air separation unit (ASU) accounts for nearly three quarters of overall efficiency loss [7].

Fig. 1 shows a schematic diagram of the CLC concept. The fossil fuel conversion is achieved in two sub-reactions (oxidation and reduction) and with oxygen carrier particle as the chemical intermediates. In the reduction stage, the oxygen carrier particle is reduced by the fuel, yielding CO_2 and H_2O. This is depicted in reaction (1) for a gaseous fuel [4]

$$(x + y/4)\ MeO + C_xH_y \rightarrow (x + y/4)\ Me + xCO_2 + y/2H_2O \qquad (1)$$

This fuel conversion step could either be exothermic or endothermic depending upon the type of oxygen carrier and fuel used. The reduced metal is then sent to the oxidizer where combustion occurs with air. The reduced metal is regenerated to its initial oxidation state as shown in reaction (2) [4].

$$Me + Air \rightarrow MeO + Oxygen\text{-}depleted\ Air + Heat \qquad (2)$$

The oxidation step being exothermic produces an enormous amount of heat which is used to generate electricity; also the fact that both the fuel and the air conversion process occur in different reactors leads to the production of a CO_2 stream from the reducer that has only H_2O as the other component, hence it is easily separated from the mixture. CLC can be applied to both gaseous (natural gas) and solid fuels (coal) [4].

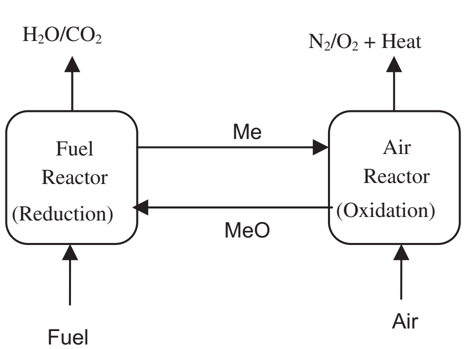

Fig. 1. Schematic of the CLC concept [4].

1.2.2. Review on CLC study

The most common metals used as oxygen carrier include Fe, Ni, and Cu. A number of promising oxygen carriers have been found, of which $NiO/NiAl_2O_4$ is perhaps the most promising [8,9]. NiO/Ni oxygen carrier particle with $NiAl_2O_4$ as inert support material will be used as the oxygen carrier particle in this study. A brief outline of some of the published work on oxygen carrier development is summarized in Table 1.

Reactor design is another important area in CLC development that has witnessed rapid growth. Optimized reactor design is required in order to render the CLC operation economically feasible. Two key factors that dictate the selection of gas–solid reactor are the type of metal oxide carriers employed for the looping operation and the type of products to be produced [4]. Fluidized beds systems have been widely applied for CLC reactor systems modelling, design and experimentation. From the pioneering work of Lyngfelt et al. [17], a number of study are available e.g. [18–20], etc. on the modelling, design and scale-up of fluidized bed reactor system for a successful operation of CLC systems.

1.2.3. CLC power cycles

In order to fully appreciate the gains of a relatively new technology such as CLC, it is imperative to carry out detailed study of its power generation potential. The CLC system can be integrated into different power cycles, and analysed at different operating conditions. These studies are done by modelling and simulation of the power plants with CLC, performing sensitivity analysis for various plant configurations in order to estimate the plant efficiency.

A number of articles have been published on the integration of CLC into power cycles. Different approaches have been adopted at different periods by different researchers to evaluate the potentials of CLC power generation scheme. Two important aspects, however dominates the researches carried out so far, these are;

- Power cycle analysis which focuses mainly on the comparative studies of different power cycles, and
- Exergy analysis of CLC power cycle and its comparison with that of conventional power cycle.

Articles focusing on the first aspect include [21–23], etc. [21–23] made use of a common fuel (CH_4) and similar oxygen carrier