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Polygeneration of hydrogen and power based on coal gasification integrated with a dual chemical looping process: Thermodynamic investigation

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ABSTRACT

This paper assesses, from a thermodynamic perspective, the conversion of coal to power and hydrogen through gasification simultaneously with a dual chemical looping processes, namely chemical looping air separation (CLAS) and water–gas shift with calcium looping CO_2 absorption (WGS-CaL). CLAS offers an advantage over other mature technologies in that it can significantly reduce its capital cost. WGS-CaL is an efficient method for hydrogen production and CO_2 capture. The three major factors, oxygen to coal (O/C), steam to coal (S/C) and CaO to coal (Ca/C) were analyzed. Moreover, the comparisons of this suggested process and the traditional processes including integrated gasification combined cycle (IGCC), integrated gasification combined cycle with carbon capture and storage (IGCC-CCS) and integrated gasification combined cycle with calcium-based chemical looping (IGCC-CaL) were discussed. And, the exergy destruction analysis of this suggested process has also been calculated.

1. Introduction

Hydrogen which gets more attentions in recent years is expected to play an important role in the future energy system due to its significant advantages, such as reducing greenhouse gas emissions and improving energy supply security. Hydrogen can be produced from various feedstock, such as natural gas, oil derived products, coal and biomass (Fan and Zhu, 2015; Mueller-Langer et al., 2007). It is clear that the reserves of coal can enable greater energy independence compared to gaseous and liquid fossil fuels (Cormos, 2009). Coal will continue to represent the backbone of the power generation sector in the coming years, but its utilization is regarded with concern because of greater greenhouse gas emissions compared to other fuels (e.g. natural gas) (Tzimas et al., 2007). Hence, where coal is used, it needs to be associated with carbon capture schemes whereby the captured carbon dioxide is stored in suitable geological formations or used for enhanced oil recovery (EOR). The integrated gasification combined cycle (IGCC) is a power generation technology, with the potential to capture carbon dioxide with low energy efficiency penalty and costs (Ahmed et al., 2015; Chiesa et al., 2005; Kabir et al., 2013; Sofia et al., 2015; Tzimas et al., 2007). In an IGCC scheme, the solid feedstock is partially oxidized by oxygen and steam to produce syngas (mainly a mixture of carbon monoxide and hydrogen). The reactions that occur during the gasification process are as follows:

Combustion reactions

$$C + O_2 \rightarrow CO_2 - 394\,kJ/mol \quad (1)$$

$$C + 0.5O_2 \rightarrow CO - 111\,kJ/mol \quad (2)$$

$$CO + 0.5O_2 \rightarrow CO_2 - 161\,kJ/mol \quad (3)$$

$$0.5O_2 + H_2 \leftrightarrow H_2O - 241.8\,kJ/mol \quad (4)$$

Boudouard reaction

$$C + CO_2 \leftrightarrow 2CO + 172\,kJ/mol \quad (5)$$

Carbon gasification

$$C + H_2O_{(g)} \leftrightarrow CO + H_2 + 131\,kJ/mol \quad (6)$$

$$C + 2H_2O_{(g)} \leftrightarrow CO_2 + 2H_2 + 90\,kJ/mol \quad (7)$$

Water–gas shift (WGS)

$$CO + H_2O_{(g)} \leftrightarrow CO_2 + H_2 - 42.4\,kJ/mol \quad (8)$$

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Nomenclature

Abbreviations

AGR	acid gas removal
AR	air reactor
Ca/C	calcium/coal
CaL	calcium-based chemical looping
CASU	cryogenic air separation unit
CCGT	combined cycle gas turbine
CCS	CO_2 capture and sequestration
CGE	cold gas efficiency
CLAS	chemical looping air separation
CLOU	chemical looping oxygen uncoupling
CTE	thermal energy of the coal used for heating the calcinations chamber-LHV
FTE	feedstock thermal energy-LHV
GO	gross electric power output
HO	hydrogen output-LHV
HRSG	heat recovery steam generator
IGCC	integrated gasification combined cycle
IGCC-CCS	integrated gasification combined cycle with carbon capture and storage
IGCC-CaL	integrated gasification combined cycle with calcium-based chemical looping
NO	net electric efficiency
O/C	oxygen/coal
RR	reduction reactor
S/C	steam/coal
TC	total ancillary power consumption
WGS-CaL	water–gas shift process with calcium looping for CO_2 sorption-enhanced
η_{gross}	gross electrical efficiency
η_{net}	net electrical efficiency
η_{H_2}	hydrogen efficiency
$\eta_{cumulative}$	cumulative efficiency
y_{H_2}	hydrogen out ratio

Reforming reaction

$$CH_4 + H_2O_{(g)} \leftrightarrow CO + 3H_2 + 206\,kJ/mol \tag{9}$$

Methanation

$$C + H_2 \leftrightarrow CH_4 - 75\,kJ/mol \tag{10}$$

After gasification process, the syngas is catalytically shifted to a high hydrogen level to concentrated carbon species into carbon dioxide, which can be later captured in a pre-combustion arrangement. The hydrogen-rich gas or the purified hydrogen that is produced after the capture of carbon dioxide and hydrogen sulfide in a double-stage acid gas removal (AGR) system is then used in a combined cycle gas turbine (CCGT) for power generation (Chiesa et al., 2005). In the conventional IGCC process, oxygen is typically derived from cryogenic air separation unit (CASU), adsorption or membranes air separation (Hashim et al., 2010; Klara and Plunkett, 2010; Pfaff and Kather, 2009; Shah et al., 2013a). As noted in the literature, CASU-based systems, including equipment, typically account for 40% of the total equipment cost or about 14% of the total oxy-fuel plant cost (Shah et al., 2013a). Although there is an approximately 10–25% expected reduction in the capital costs of adsorption and membrane air separation, both of the technologies remain expensive due to complexities related to fabrication, integration and maintenance. More importantly, the energy footprints of the adsorption-and membrane-based air separation methods are not significantly lower than those of cryogenic-based ones (Hashim et al., 2010; Klara and Plunkett, 2010; Pfaff and Kather, 2009; Shah et al., 2013a).

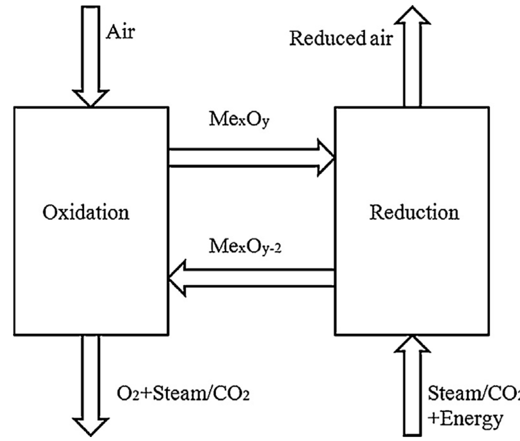

Fig. 1. Diagram of chemical looping air separation.

To achieve low-cost oxygen production, chemical looping air separation (CLAS), as a novel oxygen generation technique, has been proposed by Moghtaderi and his partners in recent years (Moghtaderi, 2009). CLAS is expected to offset 1–3% of the energy penalty that is associated with CASU, and its configuration is similar to that of chemical looping oxygen uncoupling (CLOU), whose description can be found elsewhere (Abad et al., 2012; Adanez et al., 2012; Gayán et al., 2012). The working principle behind the CLAS process is incredibly simple and involves the cyclic oxidation and reduction of metallic oxide particles as a method of separating oxygen from air. The schematic of CLAS is shown in Fig. 1. The two reactors, namely, the oxidation reactor and the reduction reactor, are linked together by a loop seal to prevent gas leakage from one reactor to another, and oxygen carriers are cycled between the twin reactors. The reduced oxygen carriers (Me_xO_{y-2}) are fed to the oxidation reactor, where oxygen from fresh air can oxidize oxygen carriers to a higher oxidation state (Me_xO_y). In the reduction reactor, the fully oxidized oxygen carriers (Me_xO_y) can release oxygen under certain conditions.

Regarding another issue of IGCC, carbon dioxide capture and storage (CCS) is an appropriate way to reduce CO_2 emissions and has been considered as a strategy for stabilizing CO_2 concentrations (Liu et al., 2015; Marchetti, 1989; Nikolaidis et al., 2015; Zaman and Lee, 2015). Several CO_2 capture technologies can be quickly deployed, and a number of emerging technologies may further help cut the cost. The post-combustion calcium looping (CaL) process, which is based on the carbonation reaction of CaO and CO_2, is one of them. Shimizu (Shimizu et al., 1999) first proposed the concept of CaL, which has been experienced rapid growth from a small-scale pilot demonstration of interconnected reactors to larger scale pilots of up to 1.7 MW_{th} (Arias et al., 2013; Charitos et al., 2010; Diego et al., 2012; Dieter et al., 2014, 2013). In a typical CaL process, CO_2 contained in the flue gas or reactors reacts with CaO particles in the carbonator unit. The reaction is shown as follows:

$$CaO + CO_2 \rightarrow CaCO_3 - 178\,kJ/mol \tag{11}$$

This carbonate is calcined in a second circulating fluidized bed. The reaction is presented as follows:

$$CaCO_3 \rightarrow CaO + CO_2 + 178\,kJ/mol \tag{12}$$

To promote the reactions of the water–gas shift process, CaL technology is introduced to WGS. The main reactions occurring in the water–gas shift reactor are as follows (Salazar et al., 2011):

$$CH_4 + H_2O_{(g)} \leftrightarrow CO + 3H_2 + 206\,kJ/mol \tag{13}$$