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Thermodynamic evaluation of chemical looping combustion for combined cooling heating and power production driven by coal

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ABSTRACT

This study carries out an investigation concerning on the benefits of ex-situ coal gasification chemical looping combustion integrated with combined cooling, heating and power generation (CCHP-CLC) by means of thermodynamic evaluation. The coal gasification syngas is introduced into chemical looping combustion for inherent separation of CO_2 without extra energy consumed. The combustion flue gases from both air reactor and fuel reactor are sequentially fed into gas turbines for electricity production, a heat recovery vapor generator unit for further electricity generation with driving a LiBr-H_2O absorption chiller for cooling production in summer and finally a heat exchanger for daily heat water production. A preliminary parameter analysis helps to obtain the optimum operating condition, as steam-to-coal ratio (S/C) of 0.05, oxygen-to-coal ratio (O/C) of 0.75, and operating pressure of chemical looping combustion process of 5 bar. The overall energy efficiency of the CCHP-CLC process is calculated equal to 58.20% in summer compared with that of 60.34% in winter. Importantly, by utilization of such process, the reduction potential of fossil fuel (coal) consumption has been demonstrated to be 23.36% in summer and 27.20% in winter.

1. Introduction

According to the IPCC, warming of the climate system is unequivocal [1]. Most of the evidences associated with the increase in global average temperature are very likely resulted from the continuous emissions of anthropogenic greenhouse gas. Among the possible candidate gases contributing to global warming (such as H_2O, CO_2, CH_4, N_2O, CFCs and SF_6), the gas considered to be contributing the most is CO_2. Cumulative emissions of CO_2 have a decisive influence on global mean surface warming by the late 21st century and beyond [2]. Globally, economic activities and population growth are the main reasons which are responsible for the increase in CO_2 emissions.

CO_2 mitigation is complementary strategy for reducing and controlling the risk of climate change. Carbon capture and storage (CCS) is taken into consideration to be a mid-term solution that is capable of offering clean energy by means of capturing CO_2 and storing it in the fossil fuel related electricity generation plants or other associated industrial plants. Approximately 90% of CO_2 emissions can be avoided to be discharged into atmosphere with the aid of CCS. However this CCS technology adds at least 10% energy penalty for CO_2 capture [3]. CCS technology significantly decreases the net efficiency and simultaneously increases the price of energy. Consequently it is urgent to develop novel low-cost or capture-free CO_2 separation methods as long-term CCS technology in the ahead years.

Fortunately, chemical looping combustion (CLC) emerges as a novel concept acceptable for inherent separation of CO_2 during combustion process without extra or with few energy required [4]. By utilization of CLC concept, the conventional combustion process is divided into two subreactions, i.e. redox reactions. Obviously, in such a nature, three benefits can be gained from CLC in comparison with conventional combustion process including: (1) due to the indirect contact between fuel and air, produced CO_2 is not diluted by N_2 and therefore separation of CO_2 is freely feasible; (2) possibility of minimizing NO_x formation is realized [5]; (3) owing to the separated subreactions, reduction of exergy destruction within CLC process has been theoretically demonstrated [6].

The journey of CLC started from 1983 when Richter and Knoche originally proposed the principle of chemical looping combustion on symposium of the American Chemical Society (ACS) [7]. Later in 1987, the name of chemical looping combustion was first given

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by Ishida and Jin [8]. Due to the concern of global warming, CLC has recently received abundant attentions as a long-term CO_2 capture method. These investigations are mainly classified into three categories: screening the suitable OCs for CLC which requires excellent thermodynamic and kinetic behaviors, low cost and low attrition; designing novel reactor configuration acceptable for CLC operation, such as fluidized bed reactor [9], alternating fixed bed [10–12] and rotating reactor [13,14]; integrating CLC into thermal cycle for electricity production.

CLC power plants by means of integrating different thermal cycles have been widely reported in literature. In 1994, Ishida and Jin made their first effort to extend the application of CH_4-fueled CLC by means of integrating CLC and air saturation (CLSA) into a novel power plant with an operational pressure of 20 bar, and the system thermal efficiency as high as 55.1% was reached [15]. Recently an extended study was conducted for investigating the economic benefits of CLAS, and the profitability index of 1.6 for the CLAS as against 1.3 for conventional humid air turbine cycle affirmed the long-term superiority of the CLAS in combating CO_2 emission over conventional combustion [16]. Subsequently, another related work associated with the pressurized H_2-fueled CLC power system was reported by Jin et al., and this system was benefited from 12 percentage-point efficiency (turbine inlet temperature of 1200 °C) compared with the H_2/O_2 combined cycle (1350 °C) [17]. Design and evaluation of a syngas-fueled CLC power plant was recently introduced by Sorgenfrei and Tsatsaronis [18] and Álvaro et al. [19], with integration of pressurized CLC system with combined cycle for power generation. Prabu proposed a novel integrated system by coupling underground coal gasification, as a clean coal technology for utilization of deep coal resource with CLC for clean-combustion for an end-use, Finally a system efficiency of 42.5% directed the thermodynamic feasibility of this concept [20]. Zhu et al. compared the power efficiency of integrated gasification combined cycle coupled with CLC (IGCC-CLC) and coupled with calcium looping process (IGCC-CLP). The IGCC-CLC was demonstrated to be thermal-beneficial compared with both IGCC-CLP and benchmark IGCC plants with CO_2 capture [21].

However, electricity is not the only requirement for the end users. For example, during the summer of 2010 in Beijing, 40% of the 16.66 million kilowatts of produced electricity was consumed for air-conditioning for cooling production [22]. For better utilization of energy, combined cooling, heating and power (CCHP) defined as the combined production of electrical, cooling and heating energy from the same primary energy source is regarded as one possible solution, which was based on the energy cascade utilization principle [23]. Compared with an electricity-only production system, the CCHP process property utilizes fossil fuel energy based on the principle of "temperature counterparts, cascade utilization".

Studies on trigeneration (i.e. electricity, cooling and heating) based on CLC concept are rarely reported. He et al. designed a solar-hybrid trigeneration system driven by dimethyl ether (DME)-fueled chemical looping combustion. As reported, the thermal efficiency was expected to be 96.7% and the global exergy efficiency was equal to be 35%. A primary energy saving ratio of 40.6% was maximized [24]. Lately, a solar-hybrid trigeneration system based on CH_4-feed CLC was first proposed by Wang et al. With $CaSO_4/CaS$ as oxygen carrier, CH_4 was fully converted into CO_2 and H_2O in the fuel reactor. Because of the use of CLC concept, zero-energy penalty was imposed on CO_2 capture. An energy efficiency and exergy efficiency of 67% and 55% was optimized in this process, respectively [25]. However, as far as we acknowledged, thermodynamic analyses on coal-fuelled CCHP system integrated with chemical looping combustion to achieve zero-energy-penalty CO_2 capture are still blank in the literature.

Inspired by this, the novelty of this work is to propose a novel combined cooling, heating and power generation system based on ex-situ coal gasification chemical looping combustion. Then parametric analyses associated with this novel process are focused on to determine the optimum operating conditions. Finally the system performances of this novel process are evaluated, to reveal the maximum benefits of this regarded process.

2. System description

The simplified diagram of coal-fuelled combined cooling, heating and power production based on chemical looping combustion (CCHP-CLC) process is shown in Fig. 1. The whole process is divided into three major subsystems, i.e. coal gasification & heat recovery, chemical looping combustion and CCHP system, with detailed description in the following sections.

2.1. Coal gasification & heat recovery

Coal gasification is a thermo-chemical conversion process which is aimed at producing clean fuels. Based on gasification process, a wide range of carbonaceous solid fuel meets the opportunity to be converted into high value gaseous fuel [26]. For the purpose of eliminating energy penalty related to CO_2 capture, the concept of chemical looping combustion is extended into coal utilization field. The simple approach to processing coal in a CLC system is utilization of an ex-situ gasification chemical looping combustion. The solid fuel is first gasified with gasification agent (such as steam or oxygen) in the gasifier to produce syngas, which is mainly constituted by CO and H_2. Following the generated syngas is directed into fuel reactor belonging to the CLC system to convert chemical energy in syngas into thermal energy contained in combustion flue gas [27].

As shown in Fig. 1, raw coal material is initially crushed into small particles, suitable for gasification. Then the prepared coal particles, mixed with pure oxygen from air separation unit (ASU) and middle-pressure steam (30 bar), are gasified into syngas by means of thermo-chemical conversion. The fresh air is first compressed to 7 bar for cryogenic air separation. In this work, complicated ASU is modelled by a black-box assumption. Within this context, the complicated module for separation of O_2 is represented by one box which owns one inlet stream and allows two outlet streams (products and waste) [28]. The amount of work required to perform separation are derived from literature, accounting for consuming 225 kW h electricity to separate 1 ton of oxygen. The separated oxygen is further compressed via three-stage intercooling compressors to meet the gasification pressure.

The high-temperature pressurized raw syngas is first cooled down through waste heat boiler (WHB) to raise three-level steams. The heated and pressurized steam is utilized to drive steam turbine (ST) for electricity generation. Subsequently, the high-pressure syngas (at the outlet of WHB) is further expanded for enhancing electricity generation. Finally the sulfur compound contained in syngas should be removed for avoiding deactivation of downstream NiO/Ni oxygen carriers in CLC prior to the syngas being cooled to 40 °C via a cooler. The separated sulfur compounds (mainly H_2S and COS) are proceeded into Claus plant to recovery sulfur. Table 1 presents the physical and chemical properties of the raw coal (Illinois #6 coal). And the main design specifications of this subunit are presented in Table 2.

2.2. Chemical looping combustion

Chemical looping combustion (CLC) is a novel technology acceptable for inherent separation of CO_2 without extra energy consumption. The conventional fuel-air combustion reaction is divided into two subreactions, which are separately occurred in