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Numerical study of mixed working fluid in an original oxy-fuel power plant utilizing liquefied natural gas cold energy

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ABSTRACT

Oxy-fuel combustion is considered one of the most promising technologies for carbon capture and storage (CCS) in power plant. The working fluid, which is composed of CO_2 and H_2O, is obligatory to moderate the combustion temperature in oxy-fuel systems. The content of H_2O in the working fluid has a significant influence on system performance. An original oxy-fuel power plant with the utilization of liquefied natural gas (LNG) cold energy is proposed, and the H_2O content in the working fluid is adjustable in the work. The results reveal that when the H_2O mass fraction is less than 0.3, the system efficiency increases with the increase of the H_2O content in the working fluid. When the H_2O mass fraction in the working fluid rises over 0.3, the system efficiency decreases with the increase of H_2O content due to the decrease of the recycling heat carried by H_2O. The optimum heat transfer effect of the recirculating H_2O is obtained when the H_2O mass fraction is 0.3, and the optimal thermal efficiency is 58.3%. Compared to dry cycle, the thermal efficiency of the proposed system is increased by 17.3% under the optimum condition.

1. Introduction

CO_2 is one of the most important greenhouse gases (GHGs) resulting from human activity due to the extensive use of fossil fuels (IEA, 2013; Olajire, 2010). Although many environment-friendly energy sources such as biomass, wind and solar have been proposed and developed as alternative energy sources (Panwar et al., 2011; Proskurina et al., 2017; Zerrahn, 2017; Manente et al., 2016), there is still a long way to go to alleviate dependence on fossil fuels.

Carbon capture and storage (CCS) technology is considered one of the most achievable technologies to reduce CO_2 emission from power plants, and it is being developed to comply with the intensification of environmental laws and policies (Fernandes-Araújo and Medeiros, 2017; Ashworth et al., 2015). Oxy-fuel combustion is regarded as a promising technology for large-scale CCS (Ghoniem, 2011; Al-Doboon et al., 2017). Compared to the conventional air combustion, the flue gas produced in oxy-fuel combustion is ready for sequestration because of the high concentration of CO_2. However, the application of oxy-fuel combustion is constrained due to the costly energy consumption in air separation unit and CO_2 capture process (Pires et al., 2011). At the state of the art of oxy-fuel combustion, the working fluid must be recycled to the combustor (COM) to moderate the high combustion temperature. According to different compositions of the working fluid in oxy-fuel combustion, the cycle mode can be divided into dry cycle (CO_2) and wet cycle (CO_2/H_2O). Some works have indicated that the system efficiency was higher in wet than dry cycles (Shaddix and Molina, 2011; Ethan et al., 2012), and more research about wet cycle is required.

Natural gas (NG) is thought to one of the cleanest energy sources from fossil fuels, and it has a considerable share in power generation. The share of the NG power generation exceeded 33% in 2016 in USA (EIA, 2016). In China, it is expected that the NG power generation load will double by 2020. Liquefied natural gas (LNG) is a common and flexible trade mode which can be transported by ships, trucks and trains. The temperature of LNG is about 110 K in tanks at the pressure of 1 bar, which is much lower than that of the ambient temperature. LNG contains enormous cold energy. Thus LNG is selected to fuel the proposed system with the use of LNG cold energy to capture CO_2 in this paper.

There are many utilizations of LNG cold energy, such as seawater desalination (Lin et al., 2017; Messineo and Panno, 2011), cold warehouses (Li et al., 2017), ocean thermal energy conversion (OTEC) system (Arcuri et al., 2015) and Kalina cycle (Wang et al., 2013). An effective utilization method of LNG cold energy is to combine it with power plant (Baris et al., 2017). Many researchers have studied the LNG oxy-fuel power plant with the utilization of LNG cold energy, such as the air separation unit (ASU) (Mehrpooya et al., 2017a,b, 2015;

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Mehrpooya et al., 2017a), flue gas cooling system and CO_2 capture (Mehrpooya and Moftakhari-Sharifzadeh, 2017c; Wu et al., 2017; Zhang et al., 2010; Alabdulkarem et al., 2012; Mehrpooya and Zonouz, 2017d). Zhang et al. (2010) presented an oxy-fuel power plant and CO_2 was selected as the working fluid. LNG cold energy was applied to liquefy the CO_2, cool down the flue gas and cool the blade of compressor. Mehdi et al. (2016) came up with a new cogeneration system which used CO_2 as the working fluid. As well as LNG cold energy, the low temperature solar energy was utilized to improve system performance. Gómez et al. (2016) put forward a novel CO_2 capture power plant employing LNG exergy. All the recoverable LNG exergy was utilized to increase the efficiency of the closed brayton cycle. Xu and Lin (2017) proposed a LNG-fired power generation system. The results showed that more than 90% of CO_2 could be captured if the flue gas temperature was less than 140 °C. The study of Xiang et al. (2018) indicated that the working fluid composed entirely of H_2O was not suitable to moderate the combustion temperature in their system because the latent heat of vaporization of the flue gas was difficult to release. The phase-transition temperature of flue gas, which is close to the boiling point of H_2O, do not meet the heat transfer requirements. As mentioned above, many different types of NG fueled oxy-fuel power plants have been studied and most of the working fluids in the studies mentioned are pure CO_2. The study of the influence of different H_2O content in the working fluid on NG oxy-fuel combustion has not been reported.

An original oxy-fuel power system is proposed and different proportions of H_2O and CO_2 in the working fluid is considered in this paper. LNG cold energy is utilized in cooling down the flue gas and liquefying CO_2 produced in combustion. The effect of H_2O content in the working fluid on the system performance is investigated. The study is fundamental to the implementation of NG oxy-fuel systems.

2. Description of the system

The layout of the original oxy-fuel power system with the utilization of LNG cold energy is shown in Fig. 1. The power cycle can be identified as 1- 2-3 -4-18-5-26-25-24-6- 7-8 -9-10-11-1. The recirculating H_2O (1) is pumped to 120 bar (2) (Ystad et al., 2013; Xiang et al., 2018), and the high-pressure H_2O is heated to gaseous state (3) by the flue gas out of the gas turbine (GT) (7). The high pressure H_2O (3) is expanded in the steam turbine (ST) to generate power and the pressure of H_2O after expansion is 30 bar (4) (Zhang et al., 2010; Deng et al., 2004; Wang et al., 2013). Then H_2O is mixed with the recirculating CO_2 (18) prior to being sent to COM. In the studies identified previously in this paper, the H_2O ratio of the working fluid in the wet cycle model was unchangeable because it was actualized by circulating the flue gas and the proportion of flue gas was fixed. The H_2O content of the working fluid in this paper is adjustable due to the original recycle design to study the effect of H_2O content in the working fluid on system performance. The temperature of COM is elevated to 1400 ℃ (Kim et al., 2011; Alhazmy and Najjar, 2004). The flue gas expands to ambient pressure in the GT to generate power (6–7). The exhaust heat of the flue gas (7) is recovered to preheat the recirculating H_2O in the heat exchanger (HX3) and heat the recirculating CO_2 (17) in sequence. Finally, the flue gas temperature is lowered to ambient after being cooled by LNG (21) in the heat exchanger (HX2). The flue gas (10) is mainly composed of H_2O and CO_2 and the liquid H_2O (11) can be removed via the separator (SEP). The excess H_2O (12) produced by the combustion of fuel is removed from power cycle.

The CO_2 capture and recycle process is defined as 13-14-15-16-27-28 and 13-14-15-16-17-18, respectively. CO_2 and other impurity gases (O_2, N_2 and Ar) (13) leaving SEP are compressed to the condensation pressure (7 bar), then CO_2 is chilled and liquefied by LNG in the heat exchanger (HX1). The low-boiling impurity gas (O_2, N_2 and Ar) is still in the gas phase, and is released from HX1. A portion of the liquid CO_2 (28) is pumped to 110 bar in the pump (P4) and captured (Christopher et al., 2016), while the other part (16) is pumped in the pump (P3). The recirculating CO_2 is preheated in the heat exchanger (HX4) before mixing with H_2O (4), and then the mixture of CO_2 and H_2O is delivered to the COM to moderate the combustion temperature.

O_2 (26) is compressed to 30 bar in the compressor (C1). The O_2 purity is supposed to be 95% (with 2% N_2 and 3% Ar) in molar concentration, which is considered as the equilibrium point between the cost of producing O_2 and cost of improving its purity (Kvamsdal et al., 2007). The energy consumption of O_2 production is set to 720 kJ/kg O_2 (Zhang and Lior, 2006; Liu and Guo, 2011). The specific composition of O_2 (26) and LNG (19) is shown in Table 1 (Wu et al., 2017; Liu et al., 2009). The value of excess O_2 coefficient is set to 1.02 in the work (Liu et al., 2009).

Apart from LNG required for combustion, more LNG is needed to ensure that all CO_2 produced in COM can be cooled to its liquefaction temperature (Mehrpooya et al., 2016; Zhang et al., 2010; Liu et al., 2009). The utilization process of LNG cold energy is 19-20-21-22-23-24.

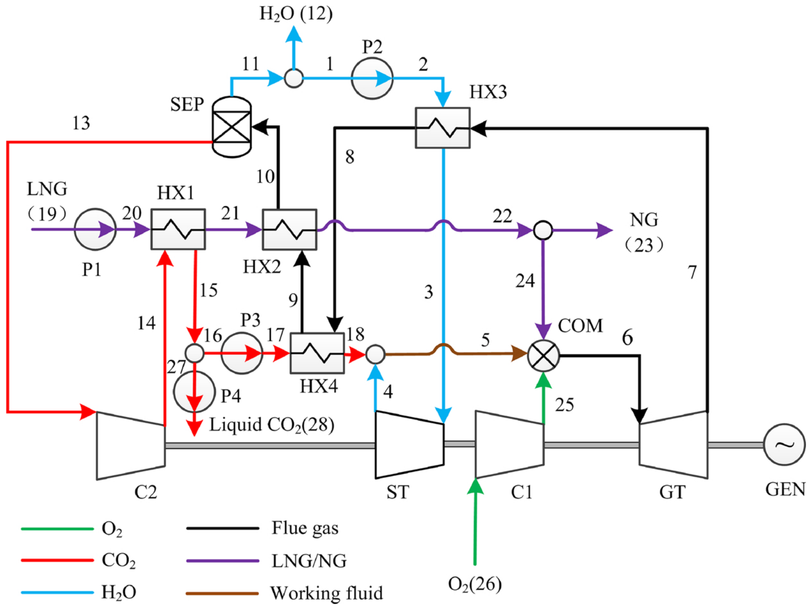

Fig. 1. The flow-process diagram of the power plant.