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Paper mills integrated gasification combined cycle process with high energy efficiency for cleaner production

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A B S T R A C T

The papermaking industry has developed rapidly in recent years in China. Papermaking is a high-energy-consuming process. Consequently, large-scale paper mills usually have cogeneration systems that supply both electricity and steam for the papermaking process. In China, almost all these cogeneration systems in paper mills are powered by coal combustion, which consumes a large amount of energy and emits large amounts of greenhouse gas. The Integrated Gasification Combined Cycle (IGCC) technology is regarded as a clean and efficient method of coal utilization. In this work, an IGCC process for application in paper mills was designed and modeled. An IGCC coupled with a cascade refrigeration process (CRP) was further proposed in order to reuse the waste heat from the dryer section and improve the energy efficiency of the papermaking process. A paper with a conventional cogeneration system, one with an IGCC cogeneration system, and one with an IGCC coupled with a CRP cogeneration system were analyzed and compared in terms of energy efficiency, capital investment, operational cost, and dynamic payback period. The results showed that the integration of IGCC technology allows paper mills to be more competitive than those featuring conventional cogeneration systems in terms of energy efficiency and operational cost.

1. Introduction

In China, the demand for paper and paperboard and consequently their production have increased rapidly in recent years. The average growth rate of the production capacity of the papermaking industry was 6% from 2006 to 2015 (China paper association, 2016). In 2015, 107.1 Mt of paper and paperboard was produced in China, accounting for 27% of the total global production (China paper association, 2016). Despite this rapid growth in the production capacity, paper consumption per person was only 78 kg, which is much less than that in developed countries (300 kg per person) (Kong et al., 2015). Consequently, the papermaking industry in China has a bright future and huge potential for development. With the increase in paper production capacity per mill, the number of paper mills decreased. There were approximately 3700 paper mills in China in 2010, which decreased to approximately 2900 in 2015 (China paper association, 2016). This indicates that the papermaking industry is developing in the direction of large-scale and highly intensive paper mills.

Papermaking is a high-energy-consumption process. The energy consumption of the papermaking industry accounts for 5% of the total industrial energy consumption (Lin and Zheng, 2017). In order to reduce its energy consumption and carbon emissions, research into reducing the energy consumption of the papermaking process is very important. Although the energy consumption per ton of paper decreased from 1.55 tce in 2000 to 1.13 tce in 2015, there remains a 15–45% energy saving potential (Peng et al., 2015). High-energy consumption also brings about problems with carbon emissions. Research has shown that the potential for the reduction of greenhouse-gas emissions in the papermaking industry in China is as high as 55% (Kong et al., 2016). Therefore, the reduction of energy consumption and carbon emissions of the papermaking industry is worthy of discussion. Consequently, China has set the goal of decreasing the energy consumption for the papermaking industry by 20% in the 13th Five-Year Plan (MIIT, 2016).

The papermaking process consumes a large amount of electricity and steam. Large-scale paper mills usually have a power plant that cogenerates electricity and steam by coal combustion. However, conventional coal-combustion power plants suffer from

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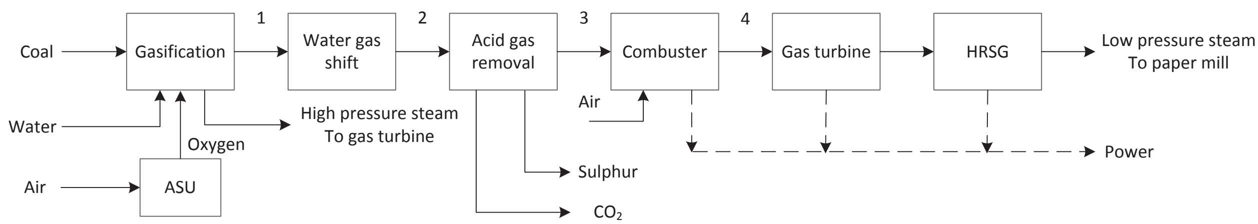

Fig. 1. Cogeneration system of IGCC.

low thermal efficiency and expensive tail-gas treatment (Yu et al., 2016). The integrated gasification combined cycle (IGCC) technology is a cleaner and more efficient power generation technology. Compared with conventional coal-combustion power generation, IGCC has higher energy and resource efficiencies and leads to lower pollution. However, high capital investment and operational costs limit the large-scale industrial application of IGCC (Ahmed et al., 2016). Research has shown that integrating IGCC power-generation systems into industrial production processes can improve their economic competitiveness (Christou et al., 2008). Therefore, an IGCC process for paper mills is proposed in this paper.

The papermaking process consumes large amounts of low-pressure steam and electricity and generates a great deal of low-temperature waste heat, which is usually unused during paper production (Leon et al., 2015). Thus, reusing this waste heat would improve the energy efficiency of the papermaking process.

With reference to the above ideas, this study presents an IGCC papermaking process with improved energy efficiency in which the waste heat of the papermaking process is reused in the cogeneration system. Modeling, simulation, and techno-economic analysis of the IGCC papermaking process are also presented in this paper.

2. IGCC process for paper mills

This paper proposes an IGCC papermaking process. There are two key elements of the new process: (1) using IGCC technology to replace high-energy-consumption coal-based cogeneration systems, and (2) reusing the low-temperature waste heat from the dryer section of the paper mill by the CRP to reduce the energy consumption of the IGCC system. In this study, the IGCC and CRP were modeled with Aspen Plus (V7.0).

2.1. Modeling and simulation of the IGCC process

A schematic diagram of the IGCC process is shown in Fig. 1. Feedstock raw coal is gasified to crude coal gas. The crude coal gas is sent to the water gas shift (WGS) unit to convert CO and water into H_2. Next, the crude coal gas is sent into the acid gas removal (AGR) unit to remove CO_2 and sulfides, and the purified H_2 obtained by this unit is sent to the combustor where it is burned with oxygen to generate high-pressure steam. The high-pressure steam is sent to a gas turbine to generate electricity. Using the heat recovery steam generator (HRSG), medium- and low-pressure steam is obtained.

2.1.1. Gasification unit

Fig. 2 shows the flowsheet of gasification in the IGCC system. In this study, British Gas/Lurgi (BGL) coal gasification technology is selected as the model for the simulation. The gasification process in the gasifier bed can be divided into five individual zones: drying, pyrolysis, gasification, combustion, and heat recovery (Yang et al., 2017).

In the drying zone, heat exchange occurs between syngas and the dropping coal, volatilizing its external moisture. The amount of vaporized water is determined by the water content in the proximate analysis of the coal. An RYield block is used to simulate dehydration of coal in the drying zone.

The dried coal is then sent to the pyrolysis zone. Coal pyrolysis produces CO, CO_2, H_2, H_2O, CH_4, H_2S, tar, and char, as shown in Eq. (1). In the model, tar is represented by C_6H_6.

$$\text{Coal} \rightarrow H_2 + CO + CO_2 + CH_4 + H_2O + H_2S + N_2 + C_6H_6 + \text{Char} \quad (1)$$

In the gasification and combustion process, homogeneous (gas-gas) and heterogeneous (gas-solid) reactions are considered, as shown in Eqs. (2)–(8) (Man et al., 2014a). Because the two reactions have different mechanisms, different kinetic expressions are needed. Table 1 lists the corresponding reaction kinetics and reaction rate constants for these reactions. The process of coal gasification is modeled using the minimum free energy of the Gibbs

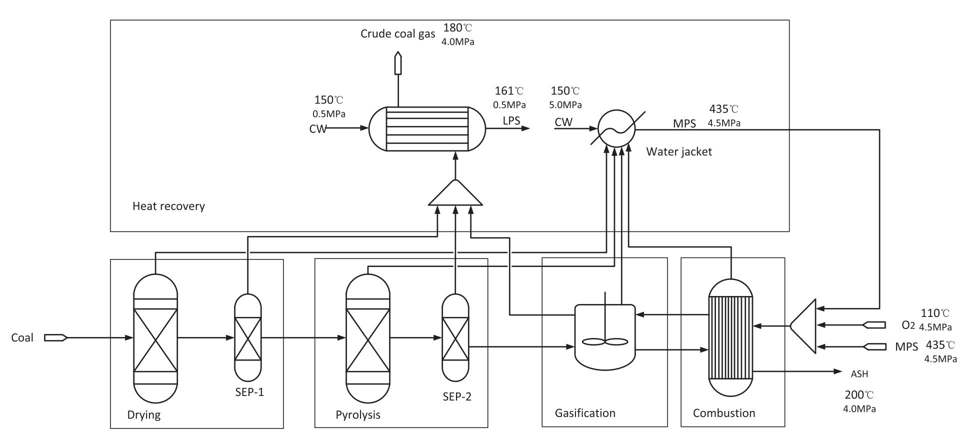

Fig. 2. Simulation flowsheet for the coal gasification unit.