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Development and techno-economic analysis of an integrated petroleum coke, biomass, and natural gas polygeneration process

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ABSTRACT

This work presents the techno-economic analysis results of a novel polygeneration process that converts biomass, petcoke, and natural gas into methanol, ethanol, DME, olefins, FT-liquids, and electricity, while eliminating CO_2 emissions. A comprehensive process simulation model was developed in Aspen Plus. The economic optimization of the plant is performed for a wide range of biomass to petcoke ratios: 0%, 5%, 10%, and 20%, using the particle swarm optimization technique. Moreover, five different optimization scenarios are considered for each feedstock including maximizing profitability of the plant, maximizing petcoke utilization, maximizing fuel production, maximizing olefin production and maximizing ethanol production. The economic optimization results showed that up to 65% of feedstock inlet can be a petcoke/biomass mixture while the process is still profitable. In addition, the results indicate that the methanol scenario leads to the minimum thermal efficiency and NPV compared to the other chemical production units.

1. Introduction

The oil industry is witnessing a steady growth in the heavy crude oil production rate. Therefore, it is not surprising that technologies that are capable of processing unconventional oils are receiving more attention in this market. However, the incorporation of traditional oil sands upgrading processes has resulted in the accumulation of the heavy residues and subsequently petcoke waste product [1,2]. The North America's petcoke production rate was around 70 million tonnes in 2011, which is more than adequate to supply the current electricity demand in Alberta, who uses a petcoke based integrated gasification combined cycle (IGCC) plants [3]. However, most of the petcoke is combusted for electricity generation or stock piled if there is no other industrial demand for them. Combustion of stockpiled petcoke, as a carbonaceous fuel, is equivalent to the carbon emissions from more than 54 million passenger vehicles [4] and thus a significant potential contributor to climate change. This is around 20% of the total number of vehicles in Canada and the United States. Thus, the development of novel petcoke upgrading technologies is an active research area.

Petcoke gasification is a widespread technology that converts petcoke to synthesis gas (syngas) [3,5,6]. The produced syngas can be upgraded to more valuable products after passing a series of treatments and downstream units [3]. Despite significant progress in petcoke gasification technologies, the profitability of such processes is still a major concern. It is mostly due to relatively high operating cost and capital investment of gasification and treatment units [5]. Furthermore, the quality of petcoke-based produced syngas, in terms of H_2/CO ratio, is much lower than the ideal values desired by chemical units [7].

Co-gasification of petcoke with other feedstocks such as biomass and municipal wastes is an alternative approach that improves the performance of the process as well as syngas quality. Municipal waste gasification has been investigated and experimentally tested in several works [8–10]. Moreover, incorporation of biomass, as a renewable gasification resource, has drawn particular attention in recent years. This option can help reduction in fossil fuel depletion, as well as CO_2 emissions [11,12]. Sofia et al. presented the experimental test results of a commercial scale coal-petcoke IGCC plant with up to 4% (weight) biomass in feedstock [13]. Their results showed that significant reduction in CO_2 emissions is possible by raising the biomass ratio. However, the mitigation cost was very sensitive to the price of biomass. In parallel, Nemanova et al. carried out a series of experiments on co-gasification of biomass and petcoke for a wide range of feedstock ratios. Their study showed that increasing the biomass percentage

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in the feedstock can reduce the activation energy of gasification reactions. It is termed the “catalytic effect” of biomass on petcoke reactivity [14]. Chmielniak et al. performed a conceptual design of methanol synthesis based on co-gasification of coal and biomass [15]. Their results illustrated that co-production of methanol and electricity can improve the efficiency and economic performance of the gasification plant. In fact, including other syngas conversion technologies such as Fischer-Tropsch (FT), methanol, ethanol, olefins, and dimethyl-ether (DME), improves the flexibility and profitability of the plant [16–22]. Huang et al. worked on the catalytic conversion of biomass to light olefins, which is a great opportunity that connects the biomass market to petrochemical industries [23]. However, the techno-economic assessment and optimization of such system based on co-gasification of biomass and petcoke, and co-production of multiple chemicals has not been in previous studies, to the best of our knowledge. Furthermore, ethanol is the other chemical product that its production from alternative fuels is an active research area [24]. Ethanol can be used as gasoline substitute for up to 10% weight without any specific problems [25,26]. Thus, in the present work, the ethanol production unit is integrated with the FT unit. It is beneficial for situations that production of gasoline is the main objective of the plant.

Combining the gasification system with natural gas reforming process is another option, which significantly reduces the syngas production cost [27–29]. Indeed, the combined gasification-reforming system can exploit the benefits of natural gas feedstock which is clean, inexpensive, and abundant. Furthermore, this novel system provides a synergy for adjusting the composition of the produced syngas based on desired values by downstream units, which cannot be achieved by standalone processes easily.

In this work, the techno-economic performance of a new integrated petcoke-biomass co-gasification system is investigated. To improve the performance and profitability of the plant, the gasification system is coupled with natural gas steam reforming. The blended syngas from gasifier and steam reformer is used in a polygeneration process. Several process variants are examined to determine the best configuration which converts petcoke to methanol, DME, transportation fuels (i.e. gasoline, diesel, and kerosene), olefins (ethylene and propylene), ethane, and electricity with minimum environmental impacts. Ethanol production from petcoke and biomass is the other innovative system that is developed and financially analyzed in the present work. The overall process also includes carbon capture to mitigate the release of greenhouse gases. A simplified block diagram of the proposed plant is given in Fig. 1.

2. Process description

The properties of the selected petcoke and biomass, as well as the composition of natural gas used for the steam reforming section, are listed in Table 1. All different cases are simulated and scaled in Aspen V8.6 based on the same combined energy of feedstocks (petcoke with biomass and natural gas) as 1400 MW (HHV) input. However, the choice of biomass with petcoke to natural gas is a decision variable within the simulation, which depends on market requirements and selected optimization scenario.

As illustrated in Fig. 1, the proposed polygeneration plant consists of 10 major units:

1. Gasification.
2. CO-rich syngas treatment and acid gas removal.
3. Natural gas reforming.
4. Fischer-Tropsch (FT) reaction for production of transportation fuel production.
5. Ethanol production.
6. Methanol production.
7. DME production.
8. Olefins production.
9. Off-gas power island.
10. CO_2 liquefaction.

In the first step, petcoke and biomass are routed to the gasification section to produce CO-rich syngas. Subsequently, the raw gas is sent to the acid gas removal unit for further treatment. The clean syngas is then blended with the produced syngas from the natural gas auto-thermal reforming unit. There are three options for the blended syngas:

1. Methanol production.
2. Ethanol production.
3. Transportation fuel production using FT process.

The produced methanol can be stored as the final product or optionally sent to DME production unit [30]. The other option for methanol product is as feed to the MTO (methanol-to-olefins) unit, which converts it to ethylene and propylene olefins [31–33]. It should be noted that the steam and electricity demand of all units are supplied by the Heat recovery steam generator (HRSG) and the power plant. The off-gas power island collects unreacted and off-gases from all units to combust them in an oxyfuel combustion boiler [19,20]. The operating conditions of each process unit are detailed in the following paragraphs. A summary of the design specifications and assumptions are listed in Table 2.

2.1. Petcoke-biomass gasification process

The selection of proper gasification technology depends mostly on feedstock type and composition. Experimental tests of various gasifiers showed that elevated pressure, entrained flow gasifiers are more suitable for less active feedstocks like petcoke [3,7]. The required residence time of entrained flow gasifiers is usually less than 10 s, which is much lower than that of fixed-bed and fluidized bed gasifiers [7]. This lower residence time can have a significant impact on the capital cost of gasification technology section [3]. Hence GE-Texaco gasifier, which is a commercial slurry-based entrained flow gasifier, is chosen for the co-gasification of petcoke and biomass in this work. The process flow diagram of the gasification and syngas treatment is illustrated in Fig. 2. The operating conditions of the GE gasifier are simulated based on process presented by Haslbeck et al., using RGibbs reactor model for the gasifier within Aspen [37]. In the proposed high-temperature, high-pressure entrained flow gasification process, ash and other incombustible materials are converted into molten slag. As illustrated in Fig. 2, this slag stream exits from the bottom of the gasifier. This high temperature stream is cooled in a water bath, which is located at the bottom of the gasifier. the downstream syngas quench and scrubbing sections capture all remaining ash. Although the slag disposal system is not modeled in this work, its cost has been included in the financial analysis of the gasification unit, based on the NETL cost analysis report [37]. The produced raw syngas is then routed to the syngas scrubber column where solid particles, Cl_2 and HCl impurities are removed. The electrolyte-NRTL model was used for this column and also the acid gas removal section [38]. The main electrolyte reactions in the syngas scrubbing column are:

$$HCl \leftrightarrow H^+ + Cl^- \tag{1}$$

$$Cl_2 + H_2O \leftrightarrow HClO + H^+ + Cl^- \tag{2}$$