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Gasification performance of various microalgae biomass – A thermodynamic study by considering tar formation using Aspen plus

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ABSTRACT

A new combined biomass and tar gasification model is developed using Aspen Plus. The proposed gasification process consists of four main units: (i) pyrolysis, (ii) combustion, (iii) gasification, and (iv) CO_2 absorption. The model predicted product compositions show good agreements (relative error < 6%) with the experimental values under similar operating conditions. The performance of the developed model is evaluated for gasification of three different microalgae species *(i) Nannochloropsis oculata, (ii) Fucus serratus, and (iii) Scenedesmus almeriensis* under various operating conditions. The parametric study is conducted by varying the amount of gasifying agents (steam and oxygen) at three different pressures (1, 40 and 80 bars). Tar from pyrolysis stage is successfully converted into syngas in the combustion zone by adjusting the oxygen flow rate (O_2 ER). The controlled use of oxygen in the combustion zone also improves the gasification performance and system efficiency. The use of steam as a gasifying agent gives high cold gas efficiency and hydrogen production. The increase of pressure has adverse effects on the gasification performance in term of syngas composition, cold gas efficiency and gasification system efficiency. The inclusion of CO_2 absorber in the gasification system provides high-quality syngas by removing CO_2. The separated pure CO_2 can be used as a feedstock for other chemical industries.

1. Introduction

The CO_2 emission from fossil fuel combustion processes is primarily responsible for climate change and global warming [1]. In order to minimize the negative impacts of fossil fuel combustions, the world communities have been searching for environmental friendly renewable energy sources and technologies [1]. In this regard, biomass from different sources, including agricultural waste, municipal waste, on purpose cultivated microalgae, are considered as potential candidates for sustainable energy sources. Recently, microalgae biomass has received growing interest as a carbon neutral clean energy source given its ability to recycle CO_2 by photosynthesis during their cultivation phase. The use of microalgae biomass also minimizes SO_x emission, as its sulfur content is significantly lower than that of fossil fuels [1,2]. However, the possibility of NO_x emission is there, as nitrogen content in the microalgae biomass is comparable to the fossil fuels [3,4]. In this regard, there are studies available in the literature investigating the minimization of NO_x emission during the conversion stages of microalgae biomass [5]. The selection of gasifying agents (CO_2, O_2) also helps minimizing the emission of NO_x formation by avoiding the contact between nitrogen and the gasified products [6]. Microalgae also offer additional advantages over other biomass sources including, high productivity, wastewater treatment by consuming nutrients, requires comparatively smaller land area per unit mass of microalgae biomass production [7].

The cultivated microalgae biomass can be either directly combusted to produce energy or gasify into permanent gases containing, H_2, CO, CO_2 and CH_4. The produced gas mixture, usually referred as syngas, can be used as a fuel in power generation, heating purpose and as a feedstock for various chemical productions, including methanol, ammonia, acetic acid etc [1]. Therefore, the gasification of microalgae biomass is considered as more efficient approach to produce energy as compared to direct combustion due to the flexibility of syngas for other purposes, resulting shorter energy pathway (less energy losses due to the conversion process) when compared to the heat energy from combustion process [8]. However, the current state of the biomass gasification technology is not ready for commercial-scale applications [9–11]. The formation of tar is one of the major issues associated with the biomass gasification. A large amount of tar is formed during the gasification step that causes severe problems in the downstream processes such as pipe

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fouling and blocking in the gas engines [12]. One way to manage fouling and blocking is the separation of tar from the gasified products. There are two common physical methods that can be used to separate tar from the product gas stream: (i) dry methods, including cyclone and filters and (ii) wet methods, including spray towers and wet cyclones. Although these methods can effectively remove tar from syngas, they cannot provide high gasification efficiency since the captured tar is disposed instead of being converted into syngas [13]. In addition, the separation of tar from the gasified stream and their disposal also requires energy [1,9]. Consequently, tar formation undermines the overall gasification efficiency significantly. Therefore, it is highly desirable to convert tar into the gaseous products.

In biomass gasification, tar formation takes place mainly in the pyrolysis step. Especially, at low temperature operations, tar formation is severe due to incomplete conversion of lignocelluosic biomass. Tar is a mixture of complex compounds and their compositions mainly depend on type of biomass, design of gasifier and operating conditions [9]. There are studies reported in the open literature dealing with tar reduction during the biomass gasification step. The common strategies for minimization of tar formation include: (i) improvement of gasifier design, (ii) adjusting the operating parameters (T, P, gasifying agent, steam/biomass ratio etc), and (iii) application of efficient catalysts. Thermal cracking of tar is not economically attractive as it requires high thermal energy for conversion of biomass and tar [1,14]. Generally, high temperature (> 800 °C) helps to minimize tar formation [13,15]. El-Rub et al. [16] reported that the phenolic-tar conversion is almost insignificant at temperature below 700 °C. The same authors showed that 97 wt% tar conversion can be achieved at 800 °C reaction temperature [16]. Phuphuakrat et al. [17] reported 78% conversion of Japanese cedar drove tar at 800 °C. The use of a suitable catalyst can facilitate higher tar conversion comparatively at lower temperature [1,18]. Although, catalyst deactivation due to coke formation and degradation of textural properties are the outstanding challenges for the catalytic tar conversion processes [10,19,20].

The reduction of tar by manipulating the gasifier configuration is an attractive strategy, which, also helps to maintain the heating value of the produced syngas. Susanto and Beenackers [21] designed a modified continuous downdraft moving bed gasifier with internal recycle. The main motivation of this gasifier was to creating high-temperature zone for thermal cracking of tar. In order to achieve high tar conversion, Susanto and Beenackers [21] divided the gasifier into four zones: (i) pyrolysis zone, (ii) combustion zone, (iii) counter-current reduction zone and (iv) co-current reduction zone. Tar from pyrolysis zone was directed to the high-temperature combustion zone to decompose them thermally. With this configuration, the authors able to reduce the tar content in the syngas below 48 mg·Nm^{-3}. Brandt et al. [22] constructed a two-stage gasifier, which produced a syngas containing 15 mg·Nm^{-3} tar.

Although the experimental study on biomass/tar gasification is important to understand the insights of the process, the experimental investigations require relatively high capital investments and they are time-consuming [23]. In this regard, thermodynamic modeling approaches are faster and significantly cheaper than the experimental works for studying the biomass/tar gasification process [24–27]. The suitable model can be applied to determine the best experimental conditions that help to save time and resources. Keeping this into consideration, last several years there are good number of thermodynamic modeling works that have been undertaken to investigate various aspects of biomass/gasification systems. Mostavi et al. [28] investigated the yield of tar, as a function of temperature, based on the equation published by Fagbemi et al. [14]. Mostavi et al. [28] assumed that the tar molecules are mainly cyclic hydrocarbons including, $C_3H_6O_2$, C_6H_6O, C_7H_8, and $C_{10}H_8$. The present research group also developed models in Aspen Plus using thermodynamic approach to investigate the performance of the modified continuous downdraft moving bed gasifier with internal recycle using different types of biomass [29].

The present study is focused on gasification of microalgae biomass integrating the conversion of tar molecules that are produced during the gasification stage. In this regard, a new gasification model is developed using Aspen Plus. The present simulation considers a downdraft gasifier with some modification on the stream flow of gaseous products and solid products in order to enhance the tar conversion. It is worth noting that downdraft gasifiers have been widely used for industrial application due to its ability to produce syngas with lower tar content than that of a updraft gasifiers [30]. As biomass feed, three different types of microalgae, including *Nannochloropsis oculata, Fucus serratus, and Scenedesmus almeriensis* species. In term of energy conversion, the performance of gasification process is determined by the cold gas efficiency and gasification efficiency [3]. The composition of the syngas, particularly the H_2/CO ratio, is an important parameter when the produced syngas is used as a feedstock of other chemical productions. For instance, the desired H_2/CO ratio of syngas for methanol synthesis is 2 (two) [31,32]. Also, the performance of the gasification system is evaluated using both steam and oxygen as the gasifying agents. The parametric study is conducted by varying the flow rates of the gasifying agents (steam and oxygen) at three different pressures (1, 40 and 80 bar) and constant flowrate of the biomass feedstocks at isothermal reaction conditions. Consequently, the heat released or required by/for the gasification system vary with the variation of gasifying agent, operating pressure and type of microalgae used as feed. It is worth noting that the present configuration offers (i) minimum tar concentration and CO_2 concentration in the syngas, (ii) producing high quality syngas and (iii) producing high-quality CO_2 for feedstock of other chemical industries (methanol synthesis) [33,34].

2. Process description

Fig. 1 represents the proposed combined gasification system, which consists of four main units: (i) pyrolysis, (ii) combustion, (iii) gasification, and (iv) CO_2 absorption. For performance analysis, three different types of microalgae biomass (*N. oculata*, *F. serratus* and *S. almeriensis*) are considered as feedstocks. The properties of these microalgae species are presented in Table 1. Steam and high purity oxygen are used as the gasifying agents. The simulations are executed for microalgae biomass feed rate of 100 kg/h to the pyrolysis zone (PY). In this zone, biomass is converted into char, volatile matters and tar. It also removes moisture from the produced char. The pyrolysis products are directed to Cyclone-1 (CYL-1) to separate solids (char and ash) and gaseous products (volatile matter, tar and water vapor). The separated solid product is sent to the gasification zone (GSF), while the gaseous product is directed to the Combustion zone (CMB). In the combustion zone, the gaseous pyrolysis products react with the gasifying agents (O_2 and steam) to give desired syngas product. A high-pressure O_2 compressor (C-1) is employed to supply oxygen, while a steam boiler (BLR) is placed to provide steam to the CMB. After reaction, the CMB product is sent to the GSF, where it reacts with the solid char received from the Cyclone-1 (CYL-1). The GSF product is sent to Cyclone-2 (CYL-2) in order to remove the unconverted char and inert ash. The separated gaseous product is depressurized in a gas turbine (TRB) and then sent to Cooler-1 (CLR-1) in order to condense the heavy fractions. The liquid is separated from the gaseous product using a Flash drum (FLS). The gaseous product from the flash drum is passed through the CO_2-absorber (ABS) to separate CO_2 from the gaseous product. The separated CO_2 is compressed in a CO_2 compressor (C-2) and sent to the storage after cooling in a Cooler-2 (CLR-2). The high purity syngas from the CO_2 absorber (ABS) is directly sent to the users. The gasification process as described above consists of the following set of chemical reactions [29]:

$$\text{Partial oxidation} \quad C + \frac{1}{2}O_2 \leftrightarrow CO \quad \Delta H^0_{298} = -111 \text{ MJ/kmol} \tag{1}$$