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Research paper

Bio-DME production based on conventional and CO_2-enhanced gasification of biomass: A comparative study on exergy and environmental impacts

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A R T I C L E I N F O

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A B S T R A C T

In this study, a novel single-step synthesis of dimethyl ether (DME) based on CO_2-enhanced biomass gasification was proposed and simulated using ASPEN Plus™ modelling. The exergetic and environmental evaluation was performed in comparison with a conventional system. It was found that the fuel energy efficiency, plant energy efficiency and plant exergetic efficiency of the CO_2-enhanced system were better than those of the conventional system. The novel process produced 0.59 kg of DME per kg of gumwood with an overall plant energy efficiency of 65%, which were 28% and 5% higher than those of conventional systems, respectively. The overall exergetic efficiency of the CO_2-enhanced system was also 7% higher. Exergetic analysis of each individual process unit in both the CO_2-enhanced system and conventional systems showed that the largest loss occurred at gasification unit. However, the use of CO_2 as gasifying agent resulted in a reduced loss at gasifier by 15%, indicating another advantage of the proposed system. In addition, the life cycle assessment (LCA) analysis showed that the use of CO_2 as gasifying agent could also result in less environmental impacts compared with conventional systems, which subsequently made the CO_2-enhanced system a promising option for a more environmental friendly synthesis of bio-DME.

1. Introduction

Biomass derived dimethyl ether (Bio-DME) is a clean synthetic fuel that has high cetane number and similar physical properties as LPG [1,2]. The combustion of bio-DME generates small amount of NOx, almost zero SOx and particulate matter. Thus, bio-DME is considered as a sustainable alternative to diesel and LPG. Compared with commercially available double-step synthesis, the single-step synthesis is a better option for DME production due to its low investment and low production costs [3,4]. Among single-step synthesis technologies developed, JFE technology, a process adopting H_2: CO ratio of 1:1 for DME synthesis, was found to be more cost-effective than other technologies, such as Hardlor Topsoe technology [1,5].

Over the past two decades, the use of CO_2 as a gasifying agent in biomass gasification has drawn increasing interests [6–8]. One of its unique features in this technology is that the H_2/CO ratio in syngas can be adjusted by controlling the amount of CO_2 injected to gasifier, despite the additional heat need to be supplied into gasifier due to the endothermic nature of reaction involved during gasification [9–11]. Recent research demonstrated that for DME production based on CO_2-enhanced gasification, the water gas shift (WGS) reactor and the energy intensive CO_2 removal process could be avoided while the production of DME could be enhanced [12]. In addition, the pure CO_2 can be easily recycled as CO_2 is a major by-product of DME synthesis. However, not much effort has yet been made to understand the exergy efficiency and environmental impacts of this novel system.

Generally, exergy analysis specifies the location, type and magnitude of process irreversibility [13–15]. It also helps better understand the benefits of energy utilization by providing more useful and meaningful information than what energy analysis could possible provide. Therefore, exergy analysis is commonly used to compare the performance of different processes, such as biomass-gasification and coal-gasification based processes [16–21]. With regard to exergy analysis of bio-DME production, to date, only a few studies have been reported [22,23]. Exergy analysis of double-step bio-DME production using steam as gasification agent was carried out by Zhang et al. [23] to measure the exergy efficiency of the entire system as well as the exergy losses occurred in each unit of the system. The reasons behind these

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losses were explored and suggestions to improve the exergy efficiency of the system were made. Recently, Xiang et al. [22] conducted the exergetic evaluation of a single-step bio-DME production from biomass where pure DME was obtained as the final product. The estimation of system exergetic efficiency and the origin of losses were also identified and quantified. Moreover, the causes of the inefficiencies were investigated and by optimising various process parameters, the higher exergetic efficiency of the system was achieved. However, in spite of the great potential of DME production based on CO_2-enhanced gasification, in depth assessment of this new route has hardly been explored due to the lack of detailed process design. To the best of our knowledge, there is not any published research on the exergetic assessment of bio-DME production using CO_2 as the gasifying agent. In addition, although life cycle assessment (LCA) is commonly used to evaluate environmental impacts of a product over its life cycle [16,24,25], the application of LCA approach for the environmental assessment of bio-DME production based on CO_2-enhanced gasification has not been reported.

This study was focused on the simulation of conventional DME synthesis system as well as DME production based on CO_2-enhanced gasification of biomass. The goal of this study was to assess the exergetic and environmental performance of bio-DME production using CO_2 as a gasifying agent. The comparison of energy, exergetic and environmental analyses between the two processes were also carried out. In addition, effort was made to show the location, magnitude and causes of the process unit inefficiencies.

2. Process description and design

2.1. Process overview

Fig. 1 shows the simplified process flow diagrams of the single-step DME production based on conventional and CO_2-enhanced biomass gasification systems. The configurations have been optimized following the guidelines proposed elsewhere [1,22,23,26,27]. In these systems, biomass feedstock is converted to syngas in a fluidized-bed gasifier, which is then conditioned prior to DME synthesis. The present work was focused on the assessment of the influence of CO_2 addition on the overall system performance.

The gasifiers for the two processes are operated under relatively different conditions. As seen in Fig. 1, the conventional process (Fig. 1a) uses oxygen and steam as the gasifying agent while the CO_2-enhanced process utilises carbon dioxide with steam. For the CO_2-enhanced biomass gasification based DME production (CEBG-DME) process, since H_2/CO ratio can be tuned by selecting proper CO_2/biomass ratio and steam/biomass ratio (as shown in Fig. 1b), the WGS and energy intensive CO_2 separation unit are eliminated. Another beneficial feature of this process is the avoidance of using of the oxygen separation unit, which could cause significant energy consumption as well as high capital and operating costs. As CO_2 is one of the main products of the single-step DME synthesis, in the CEBG-DME system, a portion of the emitted CO_2 is used in the gasifier as the gasifying agent, which helps reduce net CO_2 emission of the system. However, due to the endothermic nature of gasification reactions, additional energy is required to maintain a desired temperature in the gasifier. Since fluidized bed gasifier is used in this study, it was proposed that heat was introduced into the gasifier using an inert energy carrier. However, during simulation, electrically-heated gasifier was considered in the current study.

2.2. Biomass to syngas train

In this study, gumwood was selected as the biomass feedstock because it is widely available in China as well as in South-East Asian countries. Its properties are listed in Table 1 [28].

During gasification, the C, H, and O are transformed to CO, H_2, CO_2, and CH_4, while N and S are converted to NH_3, H_2S and COS, respectively. Since particulates (such as fly ash) that can potentially foul and/or poison the catalyst in the downstream, prior to DME synthesis, particulate matter is removed using a bag filter. A heat exchanger is used in the HRSG unit to recover waste heat to produce steam that is used in gasification unit as well as other process units. In case it is required, the recovered heat can be partly used for electricity generation, which is to meet electricity demand of the entire plant.

In conventional DME synthesis process, the gas product (syngas) is then transported to a WGS unit to adjust the H_2/CO molar ratio of 1 to satisfy the requirement for DME synthesis, followed by the purification prior to synthesis because H_2S is poisonous to the synthesis catalyst [3,29] and an excessive amount of CO_2 will reduce the conversion efficiency of DME synthesis [2,12]. In the purification section, a typical chemical absorption process with monoethanolamine (MEA) is selected to remove H_2S and CO_2, which is detailed elsewhere [30,31].

However, for CO_2-enhanced gasification based DME synthesis (Fig. 1b), the required H_2/CO molar ratio and CO_2 concentration in syngas is attained by adjusting gasification operating parameters such as temperature, CO_2/biomass ratio and steam/biomass ratio. Consequently, the WGS reaction unit and energy intensive CO_2 purification unit, the two essential steps for conventional DME production process (Fig. 1a), are avoided. It is important to note that with the addition of steam in the gasifier, WGS unit in conventional system can be avoided. However, from the perspective of an overall plant economics, this approach is not likely to be feasible, as many factors such as type of gasifier need to be considered. In order to prevent catalyst from being poisoned, only H_2S removal unit is installed.

2.3. Syngas to DME train

The purified syngas is then fed into the compressor and cooler, and subsequently introduced to the single-step synthesis reactor. As the single-step DME reaction is exothermic, to maintain an optimal reaction temperature, certain amount of heat must be removed rapidly from the reaction system, which can be utilized to generate high-pressure steam. Hence, a slurry reactor was considered in this study due to its easiness in temperature control and uniform temperature distribution [1,22]. The product stream from the synthesis reactor is cooled down and flashed so that the unreacted syngas is separated from the DME-methanol-water mixture. Afterwards, the majority of the unreacted syngas from the flash separator is recycled to DME synthesis reactor. This leads to an overall high DME conversion, while the rest of the stream was purged. The DME–methanol–water mixture contains some residual gas such as CO and CO_2, hence, it is sent to CO_2 removal unit to remove the residual gas. It is essential to note that a fraction of emitted CO_2 by the synthesis reactor is fed to the gasifier as it is used as one of the gasifying agents for the CO_2-enhanced biomass gasification. In the meantime, bottom product of the CO_2 removal unit is fed to the DME distillation unit. Distillate from this unit is taken as DME product. The methanol-water mixture, the bottom product, is sent to methanol distillation unit to separate water from methanol. The recovered methanol is also recycled to the DME reactor, whereas bottom product water, which still contained a very low amount of methanol, requires further purification. A base-case design of this study is illustrated in Fig. 1, which is for the preliminary assessment of a process design and has not yet been optimized at this stage.

2.4. Key gasification parameters

Apart from operating pressure, temperature and oxidising agent are the two important factors that dictate the composition of syngas in any gasification processes. Whilst for syngas, H_2/CO ratio and the percentage of CO_2 are the two crucial parameters that have significant impacts on its purification and application. There are other factors commonly used to evaluate gasification process, such as lower heating value (LHV) of gas product, cold gas efficiency (CGE), and gasification system efficiency (GSE) [9,10]. Moreover, for JFE single-step DME synthesis, the