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Effect of process operating conditions in the biomass torrefaction: A simulation study using one-dimensional reactor and process model

Chansaem Park, Umer Zahid, Sangho Lee, Chonghun Han*

School of Chemical and Biological Engineering, Institute of Chemical Processes, Seoul National University, Room 302-818, 1 Gwanak-ro, Gwanak-gu, Seoul 151-744, Republic of Korea

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A B S T R A C T

Torrefaction reactor model is required for the development of reactor and process design for biomass torrefaction. In this study, a one-dimensional reactor model is developed based on the kinetic model describing volatiles components and solid evolution and the existing thermochemical model considering the heat and mass balance. The developed reactor model used the temperature and flow rate of the recycled gas as the practical manipulated variables instead of the torrefaction temperature. The temperature profiles of the gas and solid phase were generated, depending on the practical thermal conditions, using developed model. Moreover, the effect of each selected operating variables on the parameters of the torrefaction process and the effect of whole operating variables with particular energy yield were analyzed. Through the results of sensitivity analysis, it is shown that the residence time insignificantly influenced the energy yield when the flow rate of recycled gas is low. Moreover, higher temperature of recycled gas with low flow rate and residence time produces the attractive properties, including HHV and grindability, of torrefied biomass when the energy yield is specified.

1. Introduction

Biomass torrefaction is a pretreatment technique involving mild pyrolysis or high-temperature drying to improve the biomass fuel quality by increasing the heating value, destroying fibrous structures, and making the surface hydrophobic [1]. The advantages of torrefied biomass have been proved by various experimental studies [2,3]. It was also reported that torrefied biomass has a potential in biomass applications. Simulation study of co-firing for torrefied biomass shown that torrefaction is able to provide a technical option for the co-firing system [4]. Torrefaction combined with densification increased performance of biomass gasification [5].

To scale up the torrefaction process for an industrial plant, a torrefaction process design is required. Fig. 1 shows the general torrefaction process scheme, where the raw biomass is dried in a predrier to reduce the moisture content before torrefaction [6]. The dried biomass is then heated by recycled gas and converted to torrefied biomass in the reactor. After torrefaction, the torrefied biomass is subjected to a size reduction process and a solid shape-forming process such as densification, depending on the application. In the reactor, the volatiles released during torrefaction have a heating value and can be utilized for combustion. This heat energy from the combustion of volatiles is used to heat the torrefaction reactor as a recycle loop in the process. A blower is used to recover the pressure drop of the recycled gas through the reactor for the recycle loop. This heat recovery component of the torrefaction process was proposed by the Energy Research Center of the Netherlands [6]. Because this heat recovery concept is expected to improve the energy efficiency of the torrefaction process and reduce the price of torrefied biomass, many recent studies on torrefaction in general and the torrefaction process in particular have been based on this concept [7].

It is essential to develop a torrefaction reactor model for process design based on this heat recovery concept, because the composition and flow rate of the volatiles and the heat released from the torrefaction reactor determine the design of all units in the process. Furthermore, the properties and quality of the torrefied product are determined using the torrefaction reactor model.

Previous works of biomass torrefaction have mainly focused on experimental research studying the effects of various operating parameters such as the temperature, residence time, feedstock, moisture contents and particle size [8,9]. Few studies on modeling of the torrefaction reaction kinetics and reactor have been

* Corresponding author. Tel.: +82 2 880 1887.
E-mail addresses: chhan@snu.ac.kr, xver@snu.ac.kr (C. Han).

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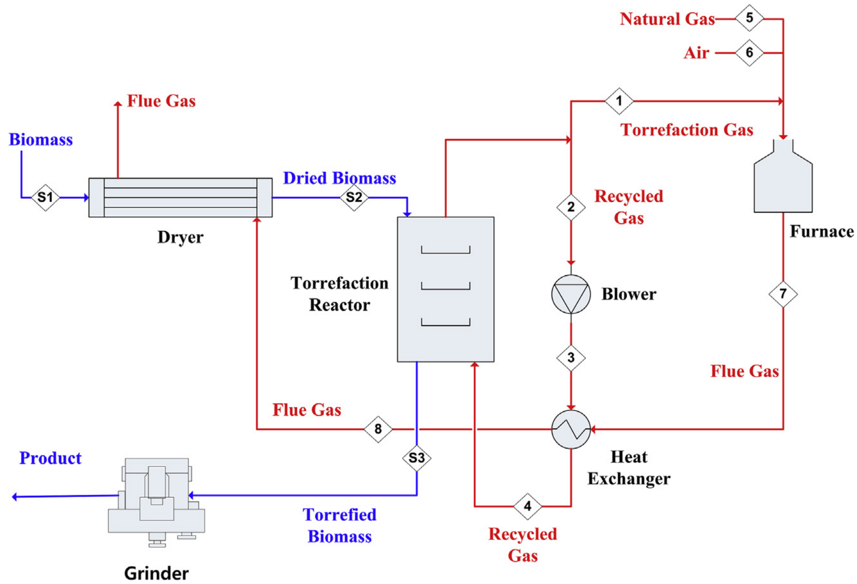

Fig. 1. Scheme of biomass torrefaction process.

performed. Research on mathematical modeling of torrefaction has mainly focused on developing a model to predict the evolution of only the solid product. For example, a kinetic model of solid evolution was developed based on willow torrefaction experiments, using a two-step, first-order torrefaction mechanism [10]. Some authors have also developed data-driven models to calculate the solid yield, based on operating parameters such as the torrefaction temperature, residence time, and initial moisture content, using mathematical regression techniques and experimental data [7,11]. However, in the development of the process design, not only a kinetic model is required to calculate the solid yield, but a model is also required to estimate the volatiles composition during torrefaction. Bates and Ghoniem [12] developed a model to predict the volatiles and solid compositions during torrefaction and validated it with experimental data. Also, a model of reaction thermochemistry is required to estimate the torrefaction enthalpy so that the accurate energy balance of the reactor can be taken into consideration. Bates and Ghoniem suggested such a thermochemical model combined with their kinetic model. In another study, the torrefaction enthalpy was estimated using a heat balance model and experimental data [13]. Recently, Peduzzi et al. proposed the model to estimate the mass and energy balance of the torrefaction unit [14]. Joshi et al. developed a tool to simulate a steady state model of the torrefaction process by linking the unit operation blocks of drying and torrefaction along with auxiliary process equipment [15]. Nikolopoulos et al. developed a process model using a commercial simulation tool to select the more efficient number of stage, temperature and residence time of the batch torrefaction reactor based on a kinetic model and mass balance only for solid phase [16].

Most torrefaction studies have regarded the reactor temperature and residence time as manipulated variables in assuming isothermal condition during torrefaction. Various experimental studies on torrefaction have used isothermal conditions, with an electric heater or furnace in the reactor [9,10], so the torrefaction status was determined based on the reactor temperature and residence time as the operating variables. Although these two variables have been considered to be crucial manipulated variables in experimental studies, excessive flow rate of heat carrier gas should be required to maintain the isothermal condition during torrefaction in the practical processes; the reactor temperature is not a manipulated variable in practical processes. As Bergman's process scheme in Fig. 1 shows, the temperature and flow rate of the recycled gas determine the temperature profile of the torrefaction reactor. The temperature profile is not able to maintain isothermal conditions when the flow rate of the recycled gas is not excessive. Thus, the flow rate and temperature of the recycled gas should be replaced by the reactor temperature as the manipulated variable. However, studies on torrefaction process using simulation have used assumption of isothermal condition for torrefaction reactor [12,14,15].

Furthermore, most of the studies on torrefaction have determined the reactor operating conditions such as temperature and residence time based only on product quality [6,17,18]. The reactor operating conditions affect the whole process design as well as the product quality. The utility and capital costs of the entire process are determined by the operating conditions. It is necessary to determine the torrefaction reactor's operating conditions considering the effects on the process design. Thus, it is necessary to develop the process model of biomass torrefaction and analyze the effect of operating conditions on its process parameters.

In this study, we developed a reactor model combining the existing kinetic model and thermochemical model of the solid yield and volatiles composition with heat transfer model for pyrolysis of biomass particle, to calculate the temperature profile in the reactor based on the mass and energy balances, considering energy balance between the heat carrier gas and biomass in the reactor. The required heat energy and information on the volatiles and product quality were evaluated using this model, considering practical operating conditions. Developed reactor model was integrated with the process model to predict the effect on the process parameters. The sensitivity analysis of operating conditions of torrefaction reactor were carried out to analyze the effect on the process design.

2. Model of torrefaction reactor

2.1. Conditions for reactor model

The base case model of torrefaction reactor was developed based on the conditions shown in Table 1. The process scheme for the base case model is presented in Fig. 1. The raw biomass is dried, and then move to the torrefaction reactor. After torrefaction, the