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Comparison of gasification performances between raw and torrefied biomasses in an air-blown fluidized-bed gasifier

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HIGHLIGHTS

- The biomass air gasification in a fluidized-bed gasifier is numerically studied.
- We directly compare the gasification behavior between raw and torrefied biomasses.
- Torrefied biomass obtains a lower H_2 yield but a higher CO yield than raw biomass.
- Raw biomass has a higher carbon conversion compared with torrefied feedstock.
- Biomass feed location has a more significant influence on torrefied fuel.

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ABSTRACT

A CFD-DEM model already developed by the authors has been extended to directly compare the gasification performances between raw and torrefied grassy biomasses in an air-blown fluidized-bed gasifier. The bed material is non-calcined olivine which acts as the solid heat carrier. Furthermore, effects of four key operating parameters (i.e., gasification temperature T_r, excess air ratio λ, steam addition, and biomass feed location) are also systematically examined. The results are analyzed both qualitatively and quantitatively by various indices: the fluidization behavior, bed pressure drop, product gas concentration profiles, total gas yield, and carbon conversion (CC). For both raw and torrefied biomasses, increasing T_r can enhance both the total gas yield and CC; rising λ decreases the H_2 yield but increases the CO_2 yield and CC; the steam addition has a positive influence on the total gas yield and CC and it can also be used to adjust the H_2/CO ratio in the product gas; both the total gas yield and CC decrease with raising the height of the biomass feed location. For all cases, the torrefied biomass obtains a lower H_2 yield and CC but a higher CO yield than its raw counterpart under the same operating conditions, suggesting that torrefied biomass requires a longer conversion process compared with raw fuel. Moreover, the gasification behavior of torrefied biomass is more dependent on the fuel feed location than raw fuel and such knowledge is important for the optimal design of fluidized-bed gasifier for torrefied feedstock.

1. Introduction

The rising concern about fossil fuel depletion and global climate change has motivated the investigation of renewable energy resources, among which biomass shows good prospects due to its abundant deposit, broad geographical distribution, and environmentally carbon–neutral behavior. Nowadays, one of the most promising technologies for biomass utilization is gasification which can convert biomasses to syngas (i.e., a mixture of CO, H_2, and CH_4) for the subsequent production of heat, power, transportation fuels, and chemical products. Regarding biomass gasification, three different types of gasifiers have been developed and practiced, i.e., fixed-bed (Warnecke, 2000), fluidized-bed (FB) (Xue et al., 2014), and entrained-flow reactors (Ku et al., 2014). Compared with other types, FB gasifiers have the main advantages of excellent gas–solid mixing, good temperature control, high rates of heat and mass transfer, and good flexibility in feedstocks (Kern et al., 2013; Shen et al., 2008). However, biomass in its raw form has a few shortcomings, such as high moisture and oxygen content, low bulk density, low energy density, and heterogeneous

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shape and size, which lead to lower conversion efficiency, storage and transportation difficulties, and utilization limitations.

In order to facilitate the industrial use of biomass, pretreatment of raw biomass is required to upgrade its quality. Among the many pretreatment methods, torrefaction has high potential to become a leading pretreatment technology (Chew and Doshi, 2011). Torrefaction is a mild thermal degradation method which heats the raw biomass to temperatures between 200 °C and 300 °C under an inert ambience, during which most of the moisture and some light volatiles are released. Consequently, the torrefied product is characterized in reduced moisture and hemicellulose content, lower O/C and H/C ratios, enhanced energy density, superior hydrophobicity, and good grindability compared with its raw counterpart. Furthermore, torrefaction can also homogenize the physical and chemical properties of raw biomass. However, there are very few publications about gasification of torrefied biomasses in real gasifiers in the literature. Couhert et al. (2009) investigated the product gas yields and reaction kinetics for steam gasification of torrefied beech in an entrained-flow reactor and found that the torrefied material produced more CO than its raw feedstock, but the char from torrefied fuel was less reactive with steam than the char from raw biomass. Fisher et al. (2012) experimentally studied the influence of torrefaction on the gasification reactivities of chars from both raw and torrefied willow and found that torrefaction greatly decreased char reactivity and its negative effect was biggest for the high-heating-rate char. Chen et al. (2013) numerically compared the gasification performance of raw bamboo, torrefied bamboo and bituminous coal in an entrained-flow gasifier. They found that the gasification behavior of torrefied biomass approached that of low-rank coal. By plotting the ratios of O/C and H/C on a Van Krevelen diagram, Xue et al. (2014) found that torrefaction improved the properties of raw miscanthus and gave a product which was similar to peat. More recently, in our previous papers (Li et al., 2015a, 2015b), the influence of torrefaction on physical properties and devolatilization performances of forest residue and spruce in a high-temperature entrained-flow reactor were experimentally studied. It was found that the particle size was decreased by torrefaction after the same grinding and sieving process and the torrefied fuel had a higher char yield than its raw counterpart. However, all the above mentioned works are confined to the fix-bed or entrained-flow reactors, and the effect of torrefaction on biomass gasification behavior in a FB gasifier has not yet been systematically studied.

Thanks to the rapid development of high-performance computers, computational fluid dynamics (CFD) models have indeed become more popular in deepening the understanding of the dense multiphase reactive flows encountered in FB reactors (Liu et al., 2015; Snider et al., 2011; Wang et al., 2009). Moreover, CFD models can also help in reactor design, scale-up, and process optimization without arduous and costly experimental campaigns. All the multiphase CFD models can be generally classified into Eulerian-Eulerian and Eulerian-Lagrangian methods. For Eulerian-Lagrangian method, gas is treated as continuous phase and particle as discrete phase (Xie et al., 2013). Furthermore, if the particle phase is resolved by discrete element method (DEM), it is also named CFD-DEM model (Kafui et al., 2002). For CFD-DEM model, each particle is individually tracked and has its own physical and chemical properties such as diameter, density, temperature, composition, and reactivity. It can also provide detailed information at the particle scale such as particle trajectory, and transient forces exerted on any particle. However, a disadvantage in CFD-DEM model is the CPU load for the intense calculations of particle collisions as the particle number enhances. Therefore, CFD-DEM modelling works are normally carried out on the order of 10^4 particles. When chemical reactions are further included, computation is more complicated and time-consuming. So far as we know, most of the CFD-DEM works carried out have only focused on the gas–solid flow dynamics of the cold fluidized bed (Ku et al., 2013; Lathouwers and Bellan, 2001; Papadikis et al., 2010) with no heat and mass transfer and chemical reactions. More recently, ‘hot’ and ‘reactive’ CFD-DEM models have been proposed to simulate the thermochemical conversion of biomass. Bruchmüller et al. (2012) used a CFD-DEM model to study biomass fast pyrolysis in a bubbling FB reactor although they did not consider chemical reactions and turbulence. A CFD-DEM model was chosen by Liu et al. (2011) to investigate char combustion in a FB reactor but their simulation settings were highly simplified, e.g., only 300 fuel particles were initially filled in and no more fuel particles were injected throughout the simulation. More recently, Gerber and Oevermann (2014) also employed a CFD-DEM model to carry out a wood gasification simulation in a FB gasifier although they used no sand or olivine as bed material which was normally adopted in real experimental campaigns. In addition, in our earlier paper (Ku et al., 2015), a CFD-DEM model for biomass gasification with steam was developed and comprehensively validated by comparing the predicted results with the experimental data. The integrated CFD-DEM model includes many submodels which account for turbulence, heat and mass transfer, radiation, particle collision and shrinkage, drying, pyrolysis, and heterogeneous and homogeneous reactions, respectively. Considering all of the existing numerical studies on biomass gasification process in a FB gasifier were exclusively conducted using raw biomasses as feedstocks, the objectives of the present paper are thus to: (1) extend the already developed CFD-DEM model for biomass steam gasification to the biomass air gasification process in a FB gasifier; (2) systematically investigate the effect of torrefaction on the biomass gasification performance under different key operating parameters (e.g., gasification temperature, excess air ratio, steam addition, and biomass feed location); (3) directly compare the gasification characteristics between raw and torrefied biomasses; and (4) explore the proper operating conditions for the gasification of torrefied feedstock. Such knowledge is very important not only for understanding the conversion process, but also for the optimal design of FB gasifier for torrefied fuels.

The paper is structured as follows: Section 2 shows a concise description of the already developed CFD-DEM model used for biomass gasification in a FB reactor. Furthermore, the char conversion and gas phase reactions as well as the reaction rates, which are applicable to biomass air gasification, are also formulated. Section 3 provides the simulation setup and the details of operating conditions. Section 4 presents the calculated results both qualitatively and quantitatively by various indicators: the fluidization behavior, bed pressure drop, product gas concentration profiles, product gas yield and carbon conversion, which highlight the effects of torrefaction and different operating parameters. In addition, the numerical model is further validated by comparing the simulation results with experimental data available in the literature. Finally, a brief conclusion is drawn in Section 5.

2. Mathematical modeling

The integrated CFD-DEM model adopted in this paper, which uses an Eulerian-Lagrangian formulation, was developed and implemented by using OpenFOAM (version 2.1.1) (OpenCFD Ltd, 2012). Details of the governing equations for both the discrete particle phase and the continuous gas phase, particle collision model, pyrolysis model, particle shrinkage model, and the numerical schemes were described in our previous paper (Ku et al., 2015). Here, only the major assumptions, a brief overview, and the chemical reactions as well as the reaction constants for biomass air gasification are presented.