Fuel Processing Technology 154 (2016) 82–90

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

# Thermodynamic equilibrium prediction of bed agglomeration tendency in dual fluidized-bed gasification of forest residues

Farzad Moradian [a,*], Placid A. Tchoffor [b,c], Kent O. Davidsson [b], Anita Pettersson [a], Rainer Backman [d]

[a] Swedish Centre for Resource Recovery, University of Borås, SE-50190 Borås, Sweden
[b] SP Technical Research Institute of Sweden, SE-50115 Borås, Sweden
[c] Chalmers University of Technology, SE-41296 Gothenburg, Sweden
[d] Department of Applied Physics and Electronics, Umeå University, SE-90187 Umeå, Sweden

ARTICLE INFO

*Article history:*
Received 28 April 2016
Received in revised form 8 August 2016
Accepted 8 August 2016
Available online 21 August 2016

*Keywords:*
Dual fluidized-bed
Bed agglomeration
Biomass
Chemical fractionation
Thermodynamic equilibrium modelling

ABSTRACT

Dual fluidized-bed (DFB) gasification is one of the recently developed technologies for production of heat, power, transportation fuels and synthetic chemicals through steam gasification of biomass. Bed agglomeration is a serious ash-related problem that should be taken into account when biomass-based fuels are selected for fluidized-bed gasification and combustion. This study developed a thermodynamic equilibrium model to assess the risk of bed agglomeration in gasification and combustion reactors of a DFB gasifier using biomass (forest residues) as feedstock. The modelling approach combined thermodynamic equilibrium calculations with chemical fractionation technique to predict the composition and melting behaviour of the fuel-derived ash as well as bed particles coating layer in the gasification and combustion reactors. FactSage was employed for the thermodynamic equilibrium calculations. The modelling results were then compared with experimental data obtained from a full-scale DFB gasifier to estimate the reliability and validity of the predictive model. In general, a good agreement was found between the modelling results and experimental observations. For the forest residues as feedstock and olivine as bed material, the modelling results indicate a low risk of bed agglomeration in the DFB gasifier, as long as the dominant temperature in the combustion zone is below 1020 °C. In contrast, quartz as bed material in the DFB gasifier was shown to significantly increase the risk of bed agglomeration through coating-induced agglomeration mechanism.



## 1. Introduction

Global warming and climate change problems associated with fossil fuels consumption have led to substantial research and development on heat and power production from alternative sources of energy. Reduction of greenhouse gas emissions, and also replacement of non-renewable resources through biomass energy utilisation has gained particular interest in recent years. Less environmental impacts and widespread availability of biomass make it an interesting option for future energy supply and demand. The conversion of biomass to bio-energy can be achieved using either biological or thermochemical processes. Combustion, gasification, and pyrolysis are the main thermochemical conversion technologies, where gasification is considered as one of the most efficient ways of converting the energy stored in biomass. Gasification is the thermal conversion of the organic fraction of solid fuels to synthesis-gas in the presence of an oxidant whose amount is lower than that required for stoichiometric combustion. Synthesis-gas (also called 'Syngas' or 'Producer gas') contains primarily carbon monoxide, hydrogen and lower amounts of methane, which can be used to power gas engines and gas turbines or as a chemical feedstock for the production of liquid fuels [1–3]. Fixed or moving bed, fluidized-bed and entrained flow are three types of gasifiers. Fluidized-bed (FB) technologies have grown to become one of the most suitable technologies for combustion and gasification of biomass. Fluidized-bed systems have a number of process advantages such as high fuel flexibility, low process temperature, emission control, high reaction rates, good gas-solid contact and mixing, and are also suitable for large-scale capacities [3–5].

Ash-related problems could be a potential problem during thermochemical conversion of biomass-based fuels. The release and transformation of inorganic species during the thermochemical processes may lead to problems, such as fouling and corrosion of heat transfer surfaces, slag formation in furnaces, as well as bed agglomeration in fluidized-bed systems. Biomass fuels can cause agglomeration of bed particles in fluidized-bed systems which results in serious problems [3,4,6]. While higher bed temperatures would enhance carbon conversion and increase tar cracking in a gasifier, the fluidized-bed temperature must be kept below the ash-fusion temperature of the biomass ash to prevent bed particle agglomeration [3]. For instance, a bubbling fluidized-bed

* Corresponding author.
*E-mail address:* farzad.moradian@hb.se (F. Moradian).

http://dx.doi.org/10.1016/j.fuproc.2016.08.014
0378-3820/

gasifier generally operates at temperatures below 900 °C to avoid bed defluidization, or even far below 900 °C for a problematic feedstock such as straw [4].

Dual fluidized-bed (DFB) gasification is one of the recently developed technologies for steam gasification of biomass. DFB steam gasification of biomass has been successfully demonstrated at the biomass power plant in Güssing, Austria (8 MWth fuel power), since late 2001. Currently, there are other plants in operation using DFB gasification technology, such as Oberwart, Austria (8.5 MWth), and Ulm, Germany (15 MWth) [7–9]. In Sweden, in the GoBiGas (Gothenburg Biomass Gasification) project, a DFB gasifier was recently being constructed to produce substitute natural gas (SNG) using biomass as feedstock. The plant currently operates with wood pellets, but the aim is to switch to a cheaper feedstock (e.g. forest residues) to make the SNG production economically feasible. Scandinavian forest-derived biomass, however, was shown to have a tendency to form bed agglomeration under fluidized-bed thermal conversion [10]. There is very limited knowledge regarding the risk of bed agglomeration in DFB gasification of forest residues. This study aims to assess the risk of bed agglomeration during DFB gasification of forest residues using thermodynamic equilibrium modelling as a predictive tool. Thermodynamic equilibrium modelling has previously been applied to predict the bed agglomeration in fluidized-bed combustors and gasifiers individually. This work introduces a new modelling approach for prediction of bed agglomeration tendency in a DFB gasification system.

### 1.1. DFB gasification

Dual fluidized-bed gasifier is a combination of a bubbling fluidized-bed (BFB) gasifier and a circulating fluidized-bed (CFB) combustor, where steam is used as gasifying agent in the BFB reactor, and air is the fluidizing and oxidising medium in the CFB reactor. Fig. 1 shows a schematic view of a DFB steam gasification process. The biomass is fluidized with steam in the gasifier at bed temperature of about 850–900 °C to produce the producer gas and residual char. Average fuel particle residence times ranging from 60 to 160 s, in the gasification zone of DFB gasifiers, have been reported [11–13]. Thereafter, the residual char is transported together with the bed material into a fast fluidized combustor (riser) via a chute, where the heat needed for endothermic gasification reactions is provided by combustion of the char at about 950–1000 °C. The hot bed materials are circulated as heat carrier between the two FBs, maintaining the required gasifier temperature.

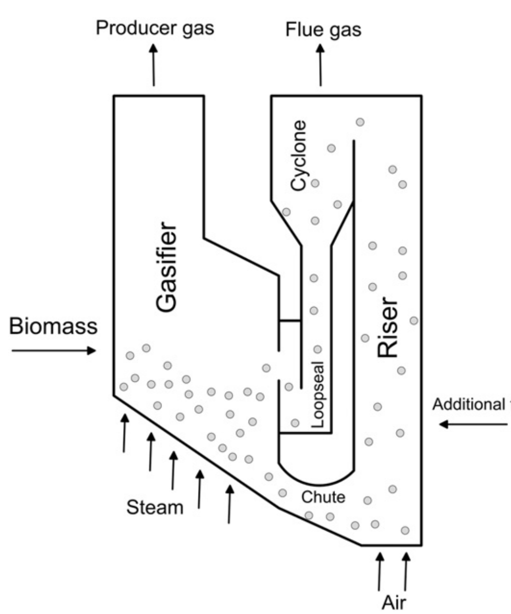


**Fig. 1.** Schematic drawing of a dual fluidized-bed steam gasifier.

Olivine and quartz are commonly used bed materials in DFB gasification plants, where olivine is most frequently used due to its catalytic properties which have shown to significantly influence the gasification properties through tar reduction in the product gas [14,15]. The embedded cyclone separates the bed materials from the flue gas, and the heated bed materials are transported to the gasifier via a loop seal. In order to prevent gas leakage between the gasification and combustion zones, and also maintain high solid throughput, the loop seal and chute are fluidized with steam. The lower temperature difference between the gasification and combustion reactors can be achieved by higher solid circulation rate, which also conveys more char to the combustor, reducing the required amount of additional fuel [4,7,8,11–16].

### 1.2. Bed agglomeration

Bed agglomeration is a serious ash-related problem in FB systems that should be taken into account when fuels are selected for FB gasification or combustion. Temperatures higher than the softening temperature of the fuel ash may result in agglomeration of bed particles and subsequently defluidization of the bed. The temperature at which the first sticky molten phases appear that are able to glue bed particles together into agglomerates is defined as initial agglomeration temperature [17]. In a gasifier, high temperatures (above 1000 °C) can enhance tar cracking into lighter species. Such temperatures, however, are incompatible with the typical operational temperature of FB gasifiers, due to the increased risk of bed agglomeration particularly in the case of feedstock with high alkali concentrations [4].

Formation of low-melting-point fuel-derived ash and/or low-melting-point coating layers on the surface of bed particles have been suggested as the most important routes for the initiation of bed agglomeration [18–22]. Partly molten fuel-derived ash can lead to direct adhesion of bed particles. This is referred to in literature as "melt-induced agglomeration" [23–25]. "Coating-induced agglomeration" refers to the formation of sticky coating layers as a result of solid-gas chemical reactions between the bed particles and gaseous species, e.g. K-compounds [18,25]. In melt-induced agglomeration the formation of partly molten ash is primarily dependent on the fuel characteristics, whereas in coating-induced agglomeration both the fuel characteristics and bed material are involved [25]. The possible bed agglomeration mechanisms during FB combustion of biomass can be either melt-induced or coating-induced, depending on the chemical composition and association of ash-forming elements in the fuel. Direct adhesion of bed particles typically takes place for fuels with ash rich in K and organically bound Si (formation of partly molten ash-derived K-silicates), and also for biomass rich in P, K and Ca/Mg (formation of partly molten ash-derived K-Ca/Mg-phosphates). For biomass with ash rich in Ca, K and relatively low amounts of Si and P, layer formation on bed particles (typical for quartz bed) can be initiated by K-silicate melt, accompanied by diffusion or dissolving of Ca into the melt, leading to viscous-flow sintering and agglomeration. Bed agglomeration as a result of direct reactions of K-compounds in gaseous or aerosol phase with quartz bed particles was suggested to be typical for biomass with high alkali content and relatively low Si and P content [19–22,26].

### 1.3. Predicting ash behaviour

For a given fuel, the elemental analysis of ash-forming matter using standard analysis methods is the starting point to determine the suitability of the fuel from the ash behaviour point of view. The standard methods, however, are not able to give information about the chemical forms of ash-forming elements in the fuel. The reactivity of ash-forming elements during the thermal processes is influenced by their chemical associations in the fuel matrix. Chemical fractionation, an advanced fuel analysis technique, can provide valuable information about the chemical association of ash-forming elements in the fuel matrix. Chemical fractionation technique can distinguish ash-forming elements into