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The influence of different parameters on biomass gasification in circulating fluidized bed gasifiers

G. Mirmoshtaghi *, J. Skvaril, P.E. Campana, H. Li, E. Thorin, E. Dahlquist

School of Business, Society & Engineering, Mälardalen University, Box 883, SE-721 23 Västerås, Sweden

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ABSTRACT

The mechanism of biomass gasification has been studied for decades. However, for circulating fluidized bed (CFB) gasifiers, the impacts of different parameters on the gas quality and gasifiers performance have still not been fully investigated. In this paper, different CFB gasifiers have been analyzed by multivariate analysis statistical tools to identify the hidden interrelation between operating parameters and product gas quality, the most influencing input parameters and the optimum points for operation. The results show that equivalence ratio (ER), bed material, temperature, particle size and carbon content of the biomass are the input parameters influencing the output of the gasifier the most. Investigating among the input parameters with opposite impact on product gas quality, cases with optimal gas quality can result in high tar yield and low carbon conversion while low tar yield and high carbon conversion can result in product gas with low quality. However using Olivine as the bed material and setting ER value around 0.3, steam to biomass ratio to 0.7 and using biomass with 3 mm particle size and 9 wt% moisture content can result in optimal product gas with low tar yield.

1. Introduction

Using biomass as the feedstock is not only driven by economic motives but also environmental and sustainability concerns [1]. Biomass such as crops, wood, grasses, agricultural and municipal waste is the renewable source of carbon and can be used to substitute fossil-based fuel and raw materials in different chemical industries [2]. Although, at the moment, biomass is not economically competitive with petroleum, policies on carbon taxes and subsidies due to sustainability can change the future for it [1].

One of the technologies to convert biomass to usable energy is gasification. In gasification there are different steps and reactions that are interrelated; some components can be both reactant and product when multiple reactions occur simultaneously. Therefore, due to the complexity of the gasification process, more investigations are required to analyze the impact of input parameters on the gas quality [2]. Although there are different studies available on analyzing gasification mechanisms, reaction kinetics and hydrodynamics of the reactor to include in system level and component level modeling [3–5], knowledge gaps still remains.

In our previous work [6], the available methods to model fluidized bed gasifiers and their performance on predicting product gas quality in different operating conditions have been thoroughly reviewed. Results show that kinetic model combined with hydrodynamic model is mostly accurate on the specific gasifiers for which the model is originally developed. While based on the review by Kersten [7] in 2001, including empirical correlations in equilibrium models can improve the accuracy of them on predicting product gas composition and therefore improves the generality of model application on different types of fluidized bed gasifiers.

Apart from review studies on modeling fluidized bed gasifiers, there are some studies on analyzing the impact of different input parameters on product gas composition. In these studies, either specific components in the product gas [8], specific gasification agent [9,10], specific type of biomass [11,12] or specific type of gasifier [13,14] have been studied. However, there is a lack of general perspective on the sensitivity of the process to input parameters when the parameters with interrelation vary simultaneously. In a previously published study on biomass gasification [15], where Principal component analysis (PCA) and Partial least square (PLS) are used as the analytical tools, the results give an overview on how parameters can affect the product gas quality. However, in this study which is done by Dellavedova et al. [15] mainly the impact of biomass characteristics on the product gas quality is

Abbreviations: n, Number of samples; PCA, Principal component analysis; PLS-R, Partial least squares regression; *RMSEP*, Root Mean Square Error in predicting validation; *b*, The regression coefficient at the cross validated given number of principle components using all the n samples; *i*, The species in the product gas; $\hat{y}_i$, Predicted Y value; y_i, Reference Y value; R^2, Coefficient of determination; $\bar{y}$, Mean of reference Y values; *Ave OE*, Average overall error.

* Corresponding author.
E-mail address: Guilnaz.mirmoshtaghi@mdh.se (G. Mirmoshtaghi).

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considered and other important parameters such as operating parameters and gasifier design are not included.

The circulating fluidized bed gasifier (CFB) is one of the suitable types of gasifiers for biomass gasification in large-scale and for production of a gas with high heating value [16] but it has not been studied as much as other types of fluidized bed gasifiers. In the past 25 years, some studies on CFB gasifiers have been done, but none of them are designed for capturing the general overview of biomass gasification in this type of gasifier.

In the present paper the focus is on CFB gasifiers and correlating several input and output parameters as well as determining the most important affective parameters on the product gas quality. This basically improves the available scientific knowledge for operating and controlling biomass gasification in CFB gasifiers. Also developing a simple empirical and statistical-based model provides the basis for predicting the impact of different operating parameters on product gas quality without including the complex physical model. This is mostly useful for the cases that there is not enough data on the specific design and operation of the CFB gasifier. The large number of included input parameters and the wide range of their variation increases the generality of the empirical model and observed correlations. For instance including different types of feedstock and the variation of ultimate and proximate analysis of the biomass increases the predictive potential of the model in more broad range of biomass species.

Additionally, doing optimization of the product gas yield by genetic algorithms (GA) and identifying optimum values for the input parameters are included. The results of this step provides the basis for optimized operation of the CFB gasifiers within the range of input parameters used in this study. In other words, results of this part can be used as best starting point for optimized operation of CFB gasifiers. Basically optimization can be done on system level and for the whole gasification process without economical evaluation [17] or with it [18] or can be performed only on a single gasifier [19]. In the optimization study by Emun et al. [17] on an integrated gasification combined cycle (IGCC) the variables with the highest impact on the results has been defined first by applying sensitivity analysis. Then the final results reveals the optimum condition for achieving the best thermal efficiency and lowest level of SOx and CO_2 emission. In another optimization study which has been performed by Kumar et al. [18] maximizing energy efficiency of a gasification plant integrated with a CHP plant is the target. The other study in optimization is performed by Asadi-saghandi et al. [19] on the novel sequential model for a BFB gasifier to maximize the efficiency of biomass gasification. This study provides the operating condition window for the specific gasifier to maximize H_2/CO ratio and accordingly efficiency of the gasifier.

In this study results from all of the available studies on biomass gasification in CFB gasifiers from the past 25 years, have been used to address the impact of different input parameters when they are varying in a wide range. As described in the review by Olofsson et al. [20], the conventional CFB gasifiers always follow the same design. However, there are some novel designs which either combine a CBF with a BFB gasifiers or two CFB gasifiers with each other as a twin bed gasifiers. These designs are not considered in the scope of this study. Other possible changes in CFB gasifiers during the time can be due to testing new bed material, feedstock or changing some operating parameters such as pressure or temperature. This type of changes have been included in this study according to the selection criteria given further in the methodology section.

The input parameters considered can be categorized in three major groups, **b**iomass characterization such as ultimate and proximate analysis of the biomass, **o**perating parameters such as temperature and gasifying agent flow and finally **g**asifier design such as the size of gasifier and bed material used in the operation. Further, the effects of different input parameters on product gas composition, carbon conversion, dry gas yield, tar yield and heating value of the product gas from biomass gasification in CFB gasifiers have been analyzed. The aim of this study is to

1. Find correlations between input parameters and product gas quality to be used for design, operation and control of biomass gasification in CFB gasifiers.
2. Determine the most important input parameters having the most significant impact on product gas quality via gasification of biomass in CFB gasifiers.
3. Find the values of the input parameters for an optimum yield of the major components in the product gas (CH_4, H_2, CO and C_2H_4), carbon conversion, heating value and dry gas yield.

By considering reactor size as one of the input parameters, the results from this paper can be used in investigations on scaling up CFB gasifiers as well.

2. Methodology

A dataset which covers a wide range of variation in input parameters are collected from previously published studies on CFB gasifiers. The input variables can be classified in three groups:

- Biomass characterization: C, H, O, higher heating value (HHV) of the biomass, moisture content (MC%), ash content (ash%), particle size
- Operating parameter: carbon to hydrogen ratio in input stream (C/H), temperature, pressure, Equivalence ratio (ER) value, steam to biomass (S/B) ratio, biomass load and biomass/reactor volume
- Gasifier design: reactor volume, bed material type

In Fig. 1, the steps used for analyzing the dataset (raw data) by statistical tools in this study are shown. First finding correlations between different input parameters and product gas quality to address the first objective is processed. Then the most affective input parameters on the product gas quality are determined to address the second objective. Finally the optimized condition to operate the CFB gasifier based on different target-gas-qualities are found to address the third objective of this study.

PCA and partial least square-regression (PLS-R) methods are selected as the multivariate statistical tools for analyzing the dataset and developing a model for further investigation and optimization. These methods have been applied to the dataset using the software Unscrambler®.

Further to model development and validation of the PLS-R model by using Genetic algorithm (GA) and varying the input parameters with the most significant impact, optimum values of the input parameters for three different output targets (I: high gas quality, II: high carbon conversion, dry gas yield and low tar yield and III: a combination of I and II) are determined.

2.1. Data collection

In this study the dataset is based on results from operation of 9 CFB gasifiers published in reports and journal papers during the past 25 years as shown in Table 1. The total number of data points used are 91 and the criteria for selecting the data sources is; ***1***. All or most of the input parameters listed in Table 2 should be considered in the data source ***2***. The reported output parameters in the data source should be gas composition, carbon conversion, heating value of the gas and dry gas yield. All CBF gasifiers used in this