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Research article

Influence of surrounding conditions and fuel size on the gasification rate of biomass char in a fluidized bed

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ABSTRACT

While the operational conditions of a fluidized bed are known to influence the fuel axial mixing, the effect of the resulting axial location of the fuel particles on the char gasification rate remains unexplored. In this work, a laboratory-scale bubbling fluidized bed was used to investigate how the gasification rate of biomass char was influenced by the fuel axial location (during pyrolysis and char gasification), the pyrolysis atmosphere, the fuel size, and the fuel concentration. When pyrolysis at the bed surface was followed by char gasification inside the dense bed the char gasification rate was up to 2-fold lower than the other combinations of the fuel axial location, which held similar rates. Cooling the char after pyrolysis decreased the char gasification rate in all cases studied. The gasification rate increased when the fuel particle size was decreased, and its dependence on the degree of char conversion was also affected. Thus, the operational conditions of a fluidized bed reactor, through modified fuel axial mixing, can influence the char gasification rate. Furthermore, experimental determination of reactivity data in laboratory-scale systems must account for the axial location of the fuel at the desired end-scale, using similar fuel particle sizes.

Nomenclature

C_b	accuracy in carbon balance (−)
HR	heating rate (°C/s)
E_a	activation energy (J/mol)
$f(X)$	structural model (−)
k_0	pre-exponential factor (s^{-1} bar^{-n})
m_0	initial mass of dry ash-free fuel (kg)
M_C	molar mass of carbon (kg/mol)
m_C	mass of carbon in fuel (kg)
$m_{C,C}$	mass of carbon measured during char combustion (kg)
$m_{C,G}$	mass of carbon measured during char gasification (kg)
$m_{ch,CG}$	mass of ash-free char in basket after char gasification (kg)
$m_{ch,f}$	mass of ash-free char fines in reactor after pyrolysis (kg)
$m_{ch,P}$	mass of ash-free char in basket after pyrolysis (kg)
$\dot{m}_{C,out}$	mass flow of carbon leaving the reactor (kg/s)
n	steam dependency (−)
$\dot{n}_{N_2}$	flow of N_2 through reactor (mol/s)
P_{reac}	partial pressure of reactant (bar)
R	gas constant (J/mol/K)
R_{ch}	char reactivity (s^{-1})
R_m	char gasification rate (s^{-1})
t	time (s)
T	temperature (K)
T_F	fuel temperature (K)
$T_{F,0}$	initial fuel temperature (K)
u_{mf}	minimum fluidization velocity (m/s)
X	degree of char conversion (−)
Y_i	molar fraction of i (mol/mol)
Y_{ch}	char yield (kg/kg daf fuel)

Acronyms

BC	boundary conditions
BET	Brunauer–Emmett–Teller
BS	on the bed surface
CG	char gasification
DFBG	dual fluidized bed gasification
F	free
FB	fluidized bed
HA	high accuracy
IB	inside the dense bed
LA	low accuracy
P	pyrolysis
SEM	scanning electron microscope
SNG	substitute natural gas
TGA	thermogravimetric analysis
WC	wood chips
WP	wood pellets

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1. Introduction

Fluidized bed (FB) biomass gasification is a promising technology for transforming lignocellulosic materials into a raw gas that can be further upgraded to transportation fuels, such as methanol, dimethyl ether, Fischer–Tropsch diesel, and substitute natural gas (SNG) [1,2]. The main advantages associated with FB units are relatively good gas-fuel mixing, even temperature distribution, and good flexibility in terms of usable fuels [3,4]. However, FB units are limited to operating temperatures below 900 °C due to the risk of agglomeration and sintering of the bed material [3,4]. Two major FB techniques can be used for biomass gasification: direct gasification, for which the heat demand is met by combusting a fraction of the fuel inside the gasification chamber [2,5]; and indirect gasification (or dual fluidized bed gasification, DFBG) [1,5]. In DFBG, unconverted char is transported with the bed material from the gasification chamber to a combustor, and the heat required for gasification is provided by recirculating the hotter bed material from the combustor to the gasifier.

The present work was carried out within the framework of the GoBiGas project [6], which aims to produce SNG on a commercial scale (80–100 MW) using DFBG. Currently, three different gasifier size scales are being used to improve understanding of the processes that occur within a DFBG system: 1) a laboratory-scale bubbling FB gasifier [7]; 2) the 2–4-MW Chalmers gasifier [8]; and 3) a 20-MW demonstration plant operated by Göteborg Energi [6]. A mathematical model of the gasifier of a DFBG system is also being developed [9], with the aim of investigating different design parameters for the optimisation and upscaling of this type of gasifier.

As discussed by Larsson et al. [8], given a specific fuel, the degree of char conversion in the gasification chamber is the main parameter that needs to be controlled for optimisation of the output of a DFBG system. Thus, for the design, up-scaling, and evaluation of a new fuel type, it is crucial to be able to predict the rate of char gasification as accurately as possible. The distinction between char reactivity and char gasification rate, see Fig. 1, should be noted. The char reactivity is a characteristic property of the char, which encompasses the kinetics (the dependency of the temperature and the concentration of the gaseous reactant), as well as structural effects (the change of the char porosity and the total surface area with the degree of conversion of the char particle, X). Furthermore, the char reactivity is also affected by a number of factors such as the ash content and composition [10] and the inhibitory effects of certain gas species [11], see below. Assuming n^{th} order kinetics, the char reactivity can be expressed as:

$$R_{ch} = k_0 \exp\left(-\frac{E_a}{RT}\right) P_{reac}^{n} f(X) \quad (1)$$

In contrast, the char gasification rate is the apparent rate, which also includes external and internal mass transfer resistances. Thus, while drying and pyrolysis (the two other conversion processes that solid fuel undergoes in a gasifier) are limited by heat transfer, the rate of char gasification is affected by several variables, including the char kinetics, the char structure, diffusional resistances, and the fuel particle size [12,13] (Fig. 1).

In order to understand how the degree of char conversion in the gasification chamber of a DFBG system is affected by different parameters, accurate modelling is a valuable tool, in which kinetic and structural parameters of quantitative relevance are key [9]. There is a vast body of literature on char reactivity. Thermogravimetric analysis (TGA) is a standard method used to investigate the reactivity of biomass char at relatively low heating rates [14,15]. Fluidized bed gasifiers have also been used in several studies aimed at investigating the reactivities of coal char [16–20] and biomass char [13,18,21–23]. In addition to determining the char kinetics, these studies have examined how the following factors influence char reactivity: fuel type [16,18,20]; surface area and porosity [16,18]; catalytic effects [18]; time of pyrolysis [16,19,20]; total pressure during gasification [19]; and partial pressure of H_2 [19]. The effects of particle size and cooling of the particles prior to char gasification have been studied [13], as well as the inhibitory effects of H_2 and CO [22]. Moreover, char gasification in mixtures of CO_2 and H_2O has received attention [22,23].

In a review published by Di Blasi [14], the activation energies for steam gasification of biomass are listed as in the range of 143–237 kJ/mol. The large variability in the kinetic parameters of biomass char is mainly due to the differences in ash content and composition of various types of biomass. For example, Ca and K have been observed to have a catalytic effect on char gasification [24–26]. However, in the presence of high concentrations of Si, K can form silicates that eventually deactivate its catalytic effects [27,28]. Furthermore, sintering of ash can block the char pores [29,30], which leads to a decrease in char reactivity. In addition to this intrinsic heterogeneity of different types of biomass, the surrounding conditions, including the heating rate and the steam-char contact during

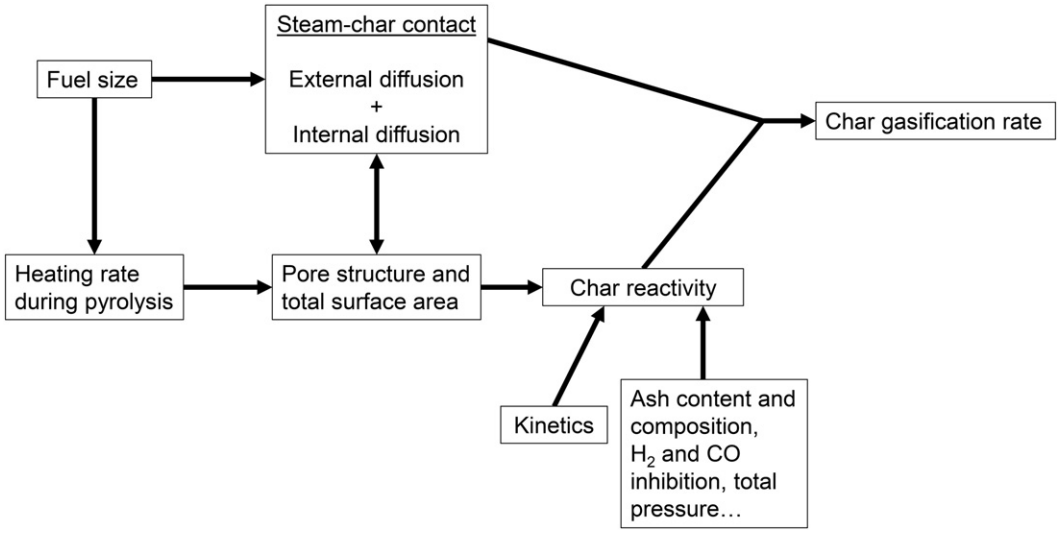

Fig. 1. Definitions of the reactivity and the gasification rate used in this work. The figure also shows how different parameters are connected to the char reactivity and the gasification rate.