Fuel 227 (2018) 256–266

Contents lists available at ScienceDirect

Fuel

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

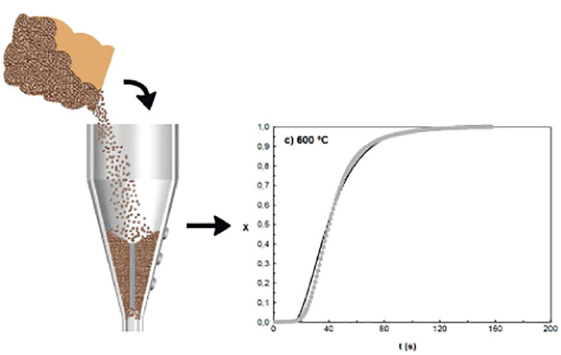
Full Length Article

Kinetic modelling of pine sawdust combustion in a conical spouted bed reactor

Juan F. Saldarriaga[a], Roberto Aguado[b,*], Aitor Atxutegi[b], Javier Bilbao[b], Martin Olazar[b]

[a] Dept. of Civil and Environmental Engineering, Faculty of Engineering, Universidad de los Andes, Carrera 1 Este N 19A – 40, Bogota, Colombia
[b] Dept. of Chemical Engineering, University of the Basque Country UPV/EHU, PO Box 644-E48080, Bilbao, Spain

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Combustion
Kinetic
Modelling
Biomass
Spouted bed

ABSTRACT

A model has been proposed and validated for the prediction of biomass combustion rate in a conical spouted bed. The model couples the intrinsic kinetics for the process and the flow pattern of the gaseous stream in the unit. The kinetics is described based on a reaction scheme consisting in simultaneous devolatilization and combustion involving the three biomass constituents, i.e., hemicellulose, cellulose and lignin. The gas flow pattern in the combustion chamber and subsequent cleaning system has been modelled using a compartimental model based on two continuous perfectly mixed vessels and a plug flow vessel. Tracer tests have been conducted to determine the residence time distribution in the whole unit and the parameters of the compartimental model. Batch combustion tests have been carried out to determine the composition of the outlet gaseous stream and the evolution of conversion with time, whose fitting to the kinetic model allowed calculating the parameters of best fit (frequency factors and activation energies). The model suitably predicts the evolution of combustion rate in a conical spouted bed, and therefore is a useful tool for the design of industrial plants based on this technology.

1. Introduction

Within the context of climate change and mitigation of the environment impact caused by human activity, biomass is one of the raw materials of greatest interest as a renewable source of energy and chemicals. In fact, at the end of the20th century the term biorefinery was coined in order to describe new types of facilities integrating biomass conversion processes to produce power, fuels and chemicals from biomass. Biomass still plays a predominant role, given that in addition to the traditional processes used since centuries, such as combustion,

* Corresponding author.
E-mail address: roberto.aguado@ehu.eus (R. Aguado).

https://doi.org/10.1016/j.fuel.2018.04.060
Received 5 December 2017; Received in revised form 11 April 2018; Accepted 12 April 2018

Nomenclature

χ_1	tracer molar fraction in the first well-mixed tank, dimensionless
χ_2	tracer molar fraction at the outlet stream, dimensionless
χ_o	tracer molar fraction at the inlet stream, dimensionless
χ_s	tracer molar fraction at the outlet of the system, dimensionless
γ	cone angle, dimensionless
D_c	column diameter, L
D_i	contactor base diameter, L
D_o	gas inlet diameter, L
E	activation energy in the Arrhenius equation, $M\,L^2\,t^{-2}\,mol^{-1}$
E_{mi}	weight stoichiometric coefficient of product i, dimensionless
f	flow rate fraction entering the second well-mixed tank, dimensionless
H_c	height of the conical section, L
k_o	frequency factor, t^{-1} or $L\,t\,M^{-1}$
k_{ci}	kinetic constant for the combustion of the char from i component, $L\,t\,M^{-1}$
k_{ref}	kinetic constant at the reference temperature, t^{-1} or $L\,t\,M^{-1}$
k_{vi}	kinetic constant for the devolatilization of i component, t^{-1}
M_i	molecular weight of product i, $M\,mol^{-1}$
n, n_{exp}	number of reaction products and number of experiments, respectively
OF	objective function, dimensionless
p_{O_2}	oxygen partial pressure, $M\,L^{-1}\,t^{-2}$
Q_1, Q_2	volume flow rates entering the first and second well-mixed tanks, respectively, $L^3\,t^{-1}$
Q_o	volume flow rate at the combustor inlet, $L^3\,t^{-1}$
Q_r	volume flow rate at the combustor outlet, $L^3\,t^{-1}$
R	gas constant, $M\,L^2\,t^{-2}\,mol^{-1}\,T^{-1}$
T	temperature, T
T_g	combustor temperature, T
T_{amb}	room temperature, T
T_{ref}	reference temperature, T
V_1,V_2	volumes of the first and second well-mixed tanks, respectively, L^3
V_T	total volume of the system, L^3
V_{CO}	CO volume injected, L^3
W, W_o	biomass mass at a given t time and initial biomass mass, M
W_{hc}, W_c, W_l, W_a	mass of hemicellulose, cellulose and lignin at a given t time and mass of ashes, respectively, M
W_{oh}, W_{ohc}, W_{oc}, W_{ol}	initial mass of moisture, hemicellulose, cellulose and lignin, respectively), M
W_{oi}, W_i	mass of polymer at the beginning and at a time t, respectively, M
X	biomass conversion, dimensionless
X_i	conversion of each polymer, dimensionless
X_{cal}, X_{exp}	calculated and experimental biomass conversions, dimensionless

sugar fermentation or carbonization, new routes have been developed over the last decades for the explotation and chemical and thermal valorisation of biomass, and substantial improvements have been carried out in certain traditional processes. Among the new routes the following are worth mentioning: production of first [1–5], second [4,6–10] and third generation biofuels [11–16], enzymatic fermentation of lignocellulosic biomass [17–20] and catalytic reforming of oxygenate hydrocarbons of biological origin for the production of paraffins [21], olefins [21–23], aromatics [24] or hydrogen [25,26]. Among the improvements of existing processes, the following are worth mentioning: increase of biomass energy density by pressing the particulate lignocellulosic biomass (pellets and briquettes) [27–29], processes for improving biomass storage and its performance in boilers by means of torrefaction [30–33], proposal of efficient reactors for the valorisaton of biomass following thermochemical routes [34–40], or the use of catalysts in pyrolysis and gasification processes [41–44] for improving the yields or selectivity of given fractions or products. Of this wide range of technologies, the integrated processes that exploit the whole biomass are especially relevant, i.e., those that not generate or at least minimize waste production. Among the processes for biomass-to-energy, combustion is at present the prevailing one, as it accounts for 90% of the world bioenergy production [45]. The choice and design of a biomass combustion system is conditioned by the physicochemical properties of the fuel, local regulations, operating and fuel costs, and by the capacity and yields required in the plant. The physicochemical properties and the performance of the fuel in the combustion chamber condition the requirements of the combustion technology, although large-scale units usually burn low quality fuels (non-homogeneous fuel concerning moisture content, particle size and ash fusion), whereas high quality fuels are preferred in small-scale units. Nowadays, fluidized bed systems are an alternative to the traditional ones based on fixed bed and grate combustors, as they have advantages, such as a more compact design of the combustor, more efficient combustion, lower NO_x emissions and considerable flexibility involving both the type of fuel and plant capacity, operating from $0.5\,t\,h^{-1}$ to $100\,t\,h^{-1}$ [46]. The spouted bed is a gas-solid technology derived from the fluidized bed, and joins the mention featured and others, such as capacity for operating with a wide particle size distribution, lower pressure drop (no distributor plate is required), lower amount of inert material in the bed and vigorous solid circulation, which ensure higher heat and mass transfer rates [47]. This technology performs well in biomass treatment processes involving both physical processes (drying [48–51]) and chemical ones (pyrolysis, oxidative pyrolysis and gasification [44,52,53]). Vegetable biomass, especially the lignocellulosic one, is suitable for combustion due to the fast devolatilization of the fuel and the high reactivity in an oxidant atmosphere of both the volatile fraction and the remaining char. The reactivity of the carbonaceous materials, both coal and biomass, has been studied using isothermal and dynamic thermogravimetry [54,55], based on different kinetic models, either unicomponent [53,56–61] or multicomponent [62–67]. Most of these studies have been carried out in thermobalance, and therefore conversion is defined based on the weight loss registered as temperature is increased. Few studies have been carried out in reaction equipment operating under similar conditions to those of real combustion systems [68,69], and there is no study carried out in a combustion unit based on the spouted bed technology. The aim of this paper is therefore to determine the kinetic parameters for the combustion of *pinus insignis* in a conical spouted bed. Accordingly, a variable should be defined for the monitoring of reactant conversion with time and proposal of a kinetic scheme that suitably describes the evolution of biomass particle in the combustion chamber. The study reported by Amutio et al. [67] will be taken as a starting point, as they operated with different oxygen concentrations in the biomass oxidative pyrolysis, in which the process is the result of pyrolysis and heterogeneous oxidation of the three main components of vegetable biomass (hemicellulose, cellulose and lignin), and combustion of the remaining char.

2. Experimental

The raw material used in this study is pinus insignis sawdust, which is representative of the lignocellulosic vegetable biomass and the most abundant and available biomass in this region. The sawdust is supplied by a local sawmill and is directly taken from one of the cutting machines in order to avoid the presence of fungicides or other types of