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Full Length Article

Experimental study of torrefied wood fixed bed: Thermal analysis and source term identification

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ABSTRACT

In this paper, self-heating scenarii were experimented on torrefied wood chips under atmospheres containing oxygen. These tests were carried out in a packed bed reactor. The experimental device was equipped with numerous thermocouples at different levels in the wood bed reactor ensuring temperature monitoring. The impact of oxygen supply was investigated at low-temperature (150 °C) both regarding oxygen content and atmosphere gas flow rate. The related results pointed out the propensity of the wood bed to self-heating particularly under a growing oxygen content or a low flow rate of oxidizing gas causing thus a spontaneous combustion. Furthermore, during self-heating, the source term was assessed relying on the local energy balance equation based on the experimental temperature fields. To summarize all results, source term values were fitted to a basic heat generation term of an oxidation reaction expressed as follows: $\Pi = \Delta H \times \epsilon \times A\exp\left(-\frac{Ea}{RT}\right) \times \rho_{O_2}^{n}$. The optimized parameter values are: $Ea = 99.8\,\text{kJ/mol}$, $A = 2.50 \times 10^{9}\,\text{s}^{-1}\left(\frac{kg}{m^3}\right)^{(1-n)}$, $n = 0.734$, $\Delta H = 14.062\,\text{MJ/kg}_{O_2}$.

1. Introduction

Today's world is becoming more conscious about environmental and social issues related to the overuse of fossil fuels. Currently, many efforts are focusing on improving the efficiency of alternative energies. Biomass is one of the most relevant renewable resources appearing as a good candidate to replace fossil fuels. Lignocellulosic biomass is intended to a thermo-chemical upgrading, through pyrolysis or gasification. These processes aim at producing solids and gases for a co-generation application and oils later upgraded to biofuels. However, some characteristics of raw biomass including its high oxygen and moisture contents besides a low calorific value weaken its energy content. These limitations, encountered even for other types of biomass, such as sewage sludge [1], can be reduced through pretreatment processes. Several pathways are followed depending on the nature of biomass and its future application. Typically, thermo-chemical conversion processes such as gasification and co-firing of lignocellulosic biomass can be preceded by a thermal pretreatment known as dry torrefaction [2,3].

Torrefaction contributes mainly in enhancing the aforementioned characteristics of raw biomass [4,5]. Torrefied biomass has then a lower moisture content, a hydrophobic nature and higher bulk density which ease its storage and transportation [2]. Furthermore, this pretreatment produces a biomass of a higher energy density. In revenge, as a result of its higher reactivity, torrefied biomass is more subjected to self-heating issues both during treatment, transportation or storage [6–8].

Self-heating is defined as a spontaneous phenomenon deriving from an unintended accumulation of heat within a reactive material. Several carbonaceous materials are affected by this situation involving mainly coal [9–11], lignocellulosic biomass [12,13] (hazelnut shells, olive pomace, wood [14–17]) and wastes (compost [18], sewage sludge [19]). Self-heating may occur as a consequence of chemical, physical or microbiological exothermic processes at low temperature. The major heat release mechanism responsible for the self-heating of the combustible material is the oxidation under oxygen exposure [11,20,8,21,22]. In some cases, thermo-chemical decomposition of biomass can cause self-heating notably during severe conditions of torrefaction [23–25]. Even at lower temperatures bacterial and fungal activity can generate heat. Several investigations of coal self-heating at low temperatures have recognized gas adsorption at the porous surface of solids as an exothermic process contributing to self-heating [10]. All

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Nomenclature

Latin symbols

A	pre-exponential factor, 1/s
c_p	specific heat capacity, J/kg/K
d	average sphere diameter, m
Ea	activation energy, J/mol
k	thermal conductivity, W/m/K
M	molar mass, kg/mol
P	pressure, Pa
Q	gas flow rate, NL/min
r	oxygen consumption rate, kg/m^3/s
R	ideal gas constant, J/mol/K
T	temperature, K

Greek symbols

ΔH	heat of reaction, J/kg
ϵ	bed porosity, –
Π	source term, W/m^3
ρ	solid phase apparent density, kg/m^3
σ	Stefan-Boltzmann constant, W/m^2/K^4

Subscripts

a	alumina
eff	effective
g	gas
p	pore
s	solid

Superscripts

i	position index
n	time index

those mechanisms combined may set a path to ignition and fire hazard. Self-heating assessment is generally linked to heat production, mass variation, oxygen consumption and gas emission. Several experimental tests have been carried out in order to measure the above self-heating indicators. The classical investigation techniques are: 1) TGA/DSC to examine the mass change and the heat flow released during the oxidation of the reactive material [21,26]. 2) Calorimetry (isothermal or adiabatic) [20] to measure more accurately the heat release rate. This approach is usually used for ranking materials according to their reactivity [11]. 3) Isothermal flow reactor to allow the measurement and the prediction of the kinetics of oxygen consumption and gas production [27,28,11,29,30]. 4) Analytical methods including FTIR, ESR/EPR to identify accurately the functional groups originating from the chemisorption of oxygen that leads to the formation of oxygenated complexes on the material surface. 5) Basket methods to predict, based on a simplified model, a critical temperature of different materials and acceptable kinetic parameters for industrial applications (Frank-Kamenetskii theory, crossing point temperature and heat release method) [16]. Furthermore, on the basis of the experimental findings, kinetic models were investigated for coal oxidation at low temperatures. The complexity of heat release processes makes their understanding limited. Hence, divergent reaction schemes were suggested to describe self-heating of coal [31,32,10,33,34].

Among the latest works concerning self-heating of wood, Evangelista et al. [35] studied this phenomenon on a packed bed reactor of torrefied wood chips submitted to oxidizing gas. Gas analysis and thermal readings reveal the exothermic tendency of torrefied wood, notably after a severe torrefaction. A qualitative approach based on gas analysis (CO, CO_2, O_2) was followed in order to detect the adsorption mechanism through oxygen balance. Neither kinetics, nor heat release related to self-heating were estimated in this study. Elsewhere, Candelier et al. [36], provided a more comprehensive pathway focused on a chemical oxidation study of thermally modified wood under oxidizing atmosphere supply. A combination of STA-DSC-FTIR analysis allowed to highlight that kinetics of degradation and oxidation of hardwood (beech) are more pronounced than for softwood (silver fir). Related heat flows were measured during oxidation and FTIR gas analysis confirmed the previous trend especially for severely heat treated hardwood. Measured heat flows were correlated with temperature, oxidation duration, mass loss and elemental compositions. However, this study didn't provide more information about wood self-heating mechanisms.

The current work aims at investigating the influence of the oxygen presence on the self-heating tendency of pretreated biomass. To this purpose, experiments were conducted in a packed bed of torrefied beech wood chips. At this scale, both physical and chemical phenomena are observed, in contrary to the particle scale experiments where only chemical reactions are meant to occur. During self-heating stage, temperature histories were analyzed and related source terms were deduced from the local energy balance at several locations inside the bed. Then, the heat source term was correlated to measured temperature and oxygen content to yield a readily usable correlation.

2. Materials and methods

2.1. Materials

2.1.1. Biomass

The beech chips used in this study were supplied by the company Sowood (Argenteuil, France). The selected chips have a regular parallelepiped shape and a relatively small size. Their equivalent diameter was measured using a caliper for 356 wood beech chips in 3D. The latter equals 3.04 mm ± 0.92 mm. The proximate and ultimate analysis of raw beech chips are given in Table 1

2.1.2. Experimental apparatus

The experiments conducted here consist of studying the propensity of self-heating at a reactor scale in a packed bed reactor of 12 L. At this scale, both physical heat/mass transfers and chemical reactions operate, in contrast with particle scale tests characterized only by chemical reactions phenomena, which is not compatible with the industrial reality. In this context, several self-heating scenarii were tested by varying some critical operating conditions.

The experimental setup drawn on Fig. 1 is composed of the following devices: 1) furnace: equipped with lateral resistances that heat the wood chips bed by radiation. 2) reactor: the reactor containing chips bed has a cylindrical shape with internal diameter of 19.6 cm and a height of 40 cm. The latter is sealed inside the furnace with a high temperature gasket. In order to monitor the temperature evolution in

Table 1
Proximate and ultimate analysis of raw beech chips.

Proximate analysis (dry basis wt.%)			Ultimate analysis (dry basis wt.%)				
Volatile matter	Fixed carbon	Ash content	C	H	O	N	S
15.2	84.3	0.5	48.76	5.98	43.93	0.35	0.96