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A weighted average global process model based on two–stage kinetic scheme for biomass combustion

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ABSTRACT

This research study combustion kinetics of four biomass samples in China, red pine (Pinus tabulaeformis), corn straw (hybrid corn Zheng Dan-958), Bermuda grass and bamboo (Phyllostachys heterocycla var), using thermogravimetric analysis (TGA). Three stages of combustion process are identified as water evaporation, removal and combustion of volatile matters and combustion of char. Thermal kinetic parameters of each sample are calculated by using 1st order Coats–Redfern method based on the TGA data. It is found that the activation energy of the global process is in the range of 53.6–65.2 kJ mol^{-1} with a poor linear correlation. The experimental data are then used to develop a two–stage reaction kinetic scheme with low temperature region (2nd stage) and high temperature region (3rd stage). The activation energy of the second stage is in the range of 123.5–140.5 kJ mol^{-1}, and that of the third stage was in the range of 59.4–93.4 kJ mol^{-1}, both of which were based on the 1st order Coats–Redfern method. Because the global process of actual combustion is different from the TGA, a modified weighted average model is proposed based on the two–stage reaction kinetic scheme. According to the modified model, the kinetic parameters of the global process for actual combustion are calculated and are all found a little smaller than that of the 2nd stages. That will benefit for the combustion simulation and the design of facility of biomass fuel.

1. Introduction

The development and utilization of biomass has recently attracted increasing attention owing to energy crisis problems. Determining how to use biomass efficiently becomes a top priority. Although biomass energy is renewable, its irrational use will waste energy thus adversely affecting the ecological environment [1,2]. Agricultural and forestry wastes, manure residues, and municipal solid wastes can generate heat and electricity directly under controlled combustion conditions. Some problems, however, exist in current biomass combustion equipments, such as low thermal efficiency, instability of heat load, and slagging [3,4]. Knowledge of the combustion kinetics of biomass is essential for understanding and modeling combustion in furnaces at industrial scale. Such knowledge is also necessary for the design and operation of conversion systems [5,6]. This has motivated a number of experimental investigations usually based on thermogravimetric analysis under oxidizing environment.

The reactivity of two kinds of biomass from Southern pine and switchgrass was investigated and results showed that both of the chars were quite reactive at early stages of char conversion [7]. The dynamic modeling of bed combustion in a BioGrate boiler furnace was developed [8] and the solid and gas phases and corresponding reactions were considered. The front reaction model was used to simulate the entire process of biomass combustion or biomass pyrolysis. A genel one-dimensional was developed to analyze the combustion of

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Table 1 – Location of biomass samples and their details.

Samples	Age (years)	Parts studied	Sampling location	Sampling time	Storage condition (Temp; humidity)	Delivery condition
Pine	9	Trunk	Langfang, China (38o52′N, 116o87′E)	7/2009	0–20 °C; 40–60%	Undried
Corn straw	0.26	Stalk Leaves	Tianjin, China (39o22′N, 117o64′E)	9/2010	0–20 °C; 40–60%	Air-dried
Bermuda grass	0.5	Leaves, Culm	Beijing, China (39o67′N, 116o23′E)	8/2010	0–20 °C; 40–60%	Air-dried, bend
Bamboo	4	Culm	Huzhou, China (31o42′N, 120o37′E)	11/2009	10–30 °C; 70–90%	Undried, pieces

different shapes of wood particles [9]. Volume reaction models are popularly used in pyrolysis. The conservation equations and kinetics were directly applied to the whole wood particle [10]. Combing a volume reaction model and front reaction approximation was proposed to simulate the combustion of a large biomass particle [11]. The multi-component models employing first order Arrhenius kinetics have proved useful in predicting the overall kinetic behavior of a biomass fuel in oxidative, reducing and inert atmospheres [12]. The combustion process of cotton stalk was interpreted in terms of two-order reactions with Arrhenius kinetics in the study on the combustion characteristics of cotton stalk in FBC [13].

Many studies are available on the kinetic properties of biomass combustion. The kinetic parameters for the global combustion process of pine needles were obtained according to Agrawal–Sivasubramanian equation [14]. Some researchers developed a two–stage reaction kinetic scheme with low and high temperature regions. The kinetic models were 1st order Coats–Redfern equation in the second stage and the diffusion mechanism in the third stage [15]. The diffusion mechanism was applied, the two–way transport and Ginstling–Brounshtein equation, respectively [16]. The 1st order Coats–Redfern equation was applied in both stages [17]. The Coats–Redfern equation was also used to solve the kinetic parameters in the two stages with reaction order of 0.5 [18].

Although different methods have been proposed in solving the dynamic parameters of biomass combustion, now no effective method has been obtained to describe the global process of biomass combustion. The 1st order Coats–Redfern model has been frequently used, however this model seems to describe biomass combustion well only in each single stage. This study will propose a modified weighted average model based on the two–stage reaction kinetic scheme to obtain the global kinetic parameters of biomass combustion. That will benefit for the combustion simulation and the design of facility of biomass fuel.

2. Materials and methods

Four kinds of typical biomass samples in China were studied in this research, including red pine (*Pinus tabulaeformis*), corn straw (hybrid corn Zheng Dan-958), Bermuda grass and bamboo (*Phyllostachys heterocycla var*). Pine is one of the most widely planted woods in China, which belongs to Sonko of coniferous evergreen trees. Hybrid corn Zheng Dan-958 is the main crop in northern China. Bermuda grass is a common lawn grass. Moso bamboo (*Phyllostachys heterocycla var*) grows in a large area in southern China. Their age, parts studied, sampling location and time, storage condition before delivery to the lab and condition during delivery are shown in Table 1.

In the laboratory, all the biomass samples were dried at room condition (20 °C) for a month before used. Each sample was crushed then placed in a drying equipment (at 60 °C) for an hour. A rotating grinder was used to mill the dried sample into millimeter–size, thus its particle diameter was less than 0.2 mm. Bituminous coal was also studied for comparison with biomass.

The properties of biomass including the moisture content, the volatile matters (VM) content, ash content, and fixed carbon (FC) content were characterized using a Muffle furnace, and high heating values (HHV) were determined by an oxygen bomb calorimeter. They were according to the standard GB/T–212–2008 (Chinese Norm) on dry basis.

Table 2a presents the testing results for both Yangquan bituminous coal (mined Yangquan, China, (38o6′N, 113o12′E)) and the four biomass samples. Biomass fuel is a combination of combustible composition, non–combustible inorganic

Table 2a – Proximate analysis and calorific values of the samples.

Samples	Mass fraction of moisture (%)	Mass fraction of volatile matters (%)	Mass fraction of ash (%)	Mass fraction of fixed carbon (%)	HHV ((MJ kg^{-1})
Bituminous coal	2.72	22.42	29.16	45.70	24.33
Red pine	5.80	77.70	3.45	13.05	17.16
Corn straw	5.47	68.04	15.37	11.12	14.71
Bermuda grass	5.22	74.26	9.80	10.71	15.65
Bamboo	5.16	79.12	2.63	13.08	17.34