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A two dimensional model for torrefaction of large biomass particles

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ABSTRACT

Torrefaction is defined as a thermal pre-treatment process performed within a temperature range of 200–300 °C, at low-heating rates (<20 °C/min) and for residence times between 15–60 min in inert environments. A phenomenological model of the torrefaction process of large biomass particles is developed in this work. Mass and energy balance coupled to a kinetic model take into account two steps of the biomass decomposition. First of the two steps, considers simultaneous production of vapor and solids from raw biomass. The vapor phase comprises a mixture of condensable and non-condensable gases, while the solid phase consists of torrefied biomass. The second step involves decomposition of volatiles into gases and secondary char. The model analyzes torrefaction behavior of both large and small biomass particles, predicting their final solid and gas yields, temperatures distribution, internal pressure and velocity of the gas phase within the particles. The model also predicts maximum conversions for given particle sizes and temperatures during the process. For given set of conditions small particles showed higher (~77%) than that (~52%) for large particles. Maximum interstitial gas velocities inside the large particle (25 mm in diameter and 65 mm in length) was about 1.2 mm/s and pressure gradients of about 2000 kPa and it occurred after 20 min in the process.

1. Introduction

Biomass is a promising source of solid fuels that could compete with fossil fuels like oil and coal because of its low emissions of greenhouse gases and their acceptable performance in thermal processes. Despite the benefits of using biomass in thermal processes, its implementation is hindered due to high moisture content and low energy density of biomass. The projects feasibility is compromised due to the cost associated with transport and handling of large volumes of biomass. Therefore only small and medium scale projects may provide an option for obtaining economic benefits of the biomass thermal transformation.

The torrefaction process, defined as a thermal pre-treatment performed in the temperature range of 200–300 °C, with low heating rates (<20 °C/min), and over residence times ranging from 15–60 min in inert environments or with low oxygen concentrations [1]. During the torrefaction process, the biomass undergoes a mass loss of up to about 40% and an energy loss of 10–15%, resulting in a biomass with higher specific energy, of brittle nature requiring low energy for grinding process, and hydrophobic (the amounts of moisture absorbed after the process can be around 3%). Additionally, it provides a product uniform in quality, with higher energy density and resistant to decomposition by exposure to the environment [2–4].

The lignocellulose biomass is composed mostly of hemicellulose, cellulose, and lignin, which, during the thermal process degrades, generating gases, tars and a torrefied solid. Hemicellulose decomposes thermally in the temperature range of 150–350 °C, cellulose is decomposed in the temperature range of 275–350 °C, and lignin decomposes in the temperature range of 250–500 °C [1]. Much of the hemicellulose structure is broken down during the torrefaction process, while cellulose and lignin suffer a minor decomposition depending on the treatment conditions performed [5].

Many research works on torrefaction have been carried out in the experimental field, where different kinds of biomass are torrefied under different operational conditions [2,6–13]. In these experimental works, the operating conditions of the torrefaction process are proposed intuitively in order to find those that can produce the best final properties of torrefied biomass. A phenomenological model can describe the chemical and physical phenomena occurring in the process and thereby provide the optimum operating condition for the best final properties of the torrefied biomass.

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Currently in the literature, the information about predictive models in the field of torrefaction is rather limited [14–19]. These models consider the influence of physical phenomena, such as heat transfer between phases, and chemical reactions studied through global kinetics for biomass decomposition [20–23]. Some [24,25] also consider decomposition of individual components like hemicellulose, cellulose, and lignin. Most of these kinetic models, however, did not consider the formation of secondary char from condensable volatiles generated in the devolatilization process [26]. The initial steps of torrefaction could involve pyrolysis and gasification. These processes are extensively studied in the context of combustion of coal resulting in an accurate description of the kinetics and complete models of different kinds of coals. Latter studies on torrefaction process have taken advantage of much of the knowledge and advances developed in the field of pyrolysis [27–36] for structuring models and describe the torrefaction process in a biomass.

Chan et al. [28] developed a model for a biomass particles subjected to heating in an inert atmosphere. The model considered drying of the particle, volatiles generation and its secondary reactions. Conduction and convection processes inside the particle and variation of properties with temperature are considered. A decomposition model that considers solid formation, gas, tar and secondary tar decomposition was included in the model. This torrefaction model predicted the compositions of the final products.

Generally, biomass particles are considered an isotropic solid with properties varying in the thermal process. Di Blasi [37] modeled a biomass particle in two dimensions which is heated in an inert atmosphere at a controlled heating rate. In this model, conduction and convection heat transfer within the particle and convection and radiation with external systems outside of the particle were considered. They used a kinetic decomposition model for biomass without considering secondary reactions between tar and solid. This model can predict temperature profiles, speed of gas and char production. Results were compared with simulations of one-dimensional models and found comparable results [38–40].

Felfi et al. [41] developed a phenomenological one-dimensional transient model applied to the torrefaction of a wood pellet. This model considered that the volatiles and steam generated in the process are in thermal equilibrium with the solid. Geometrical changes of the solid and pressure gradients during the torrefaction process are considered negligible due to the high permeability of the solid. The kinetic model used in this model was proposed by Shafizadeh and Chin [42] which considers that biomass is decomposed by three competitive reactions to gas, tar, and char. This model reproduced the process of drying, and heating of the particles, and volatile production. This model is, however, not sufficiently explicit about the phenomena occurring inside the particle.

Ratte et al. [19] proposed a phenomenological one-dimensional transient model for the slow pyrolysis of spherical wood particles. In this model the average volume simplification proposed by Whitaker [43] was used. Mass and energy balances were performed for the particles considering the kinetic model proposed by Shafizadeh and Chin [42]. With this model, it is possible to reproduce the temperature distribution inside the particle, moisture content and pressure increase due to the generation of volatiles over time. This model was more rigorous than that considered by Felfi et al. [41], but the kinetic model still did not consider the secondary char formation from heterogeneous reactions between volatiles and char.

Turner et al. [44] modeled the torrefaction process of wood using a two-dimensional phenomenological transient model. In this model chemical and physical phenomena are coupled using the "Transpore" model developed earlier by Perré and Turner [45] that describes the drying process in a porous medium. The kinetic model used is centered on the hypothesis that decomposition of biomass can be described as decomposition of each component (cellulose, hemicellulose and lignin). Again, in this "Transpore" model, the secondary char formation from volatiles was not considered.

Pétrissans et al. [46] modeled the thermal degradation of wood particles with a one-dimensional transient model. This model neglected energy transfer by convection between the solid and the volatiles generated inside the particle. The decomposition of wood was represented by two simultaneous reactions which generate gas and char. The main focus this work was the formation of primary char. It did not provide any information about formation of other products.

Ratte et al. [14] developed one of the few models found in the literature applied for a continuous torrefaction reactor. Two phases were considered inside the reactor: a particles phase composed of biomass and a continuous phase composed of 11 species present in the gases entering the reactor and generated in the process. The kinetic model considers only the formation of volatile and char without considering the secondary reactions in the heterogeneous phase. Eight reactions were considered to represent the secondary reactions in the homogeneous phase during the torrefaction process.

According to the above literature review of modeling of torrefaction process, it is clear that the available information about secondary reactions describing the secondary formation of a solid or char is scarce. Despite the low production of secondary char in the torrefaction process, it plays an important role, and understanding its formation is an ongoing challenge. The present work attempts to develop a phenomenological model of the torrefaction process with a kinetic model presented by Basu et al. [17] that considers the formation of secondary char and condensable and non-condensable volatiles. The model is able to predict the behavior of a biomass particle in kinetic control conditions and large particles in a torrefaction process.

2. Model description

This section presents a transient 2D model for the torrefaction process of a biomass particle. This model is applied over the system shown in Fig. 1 for a vertical biomass particle. The model considers the drying and devolatilization stages of the biomass occurring in the sequence shown in Fig. 2.

This model predicts the behavior of the biomass sample undergoing torrefaction in an heated vertical kiln type reactor. Particle heating is through radiation from the kiln walls in which the sample is torrefied. During the initial heating stage, drying of the particle occurs, and thereafter the devolatilization process starts at temperatures of about 180 °C with hemicellulose decomposition (Fig. 2). The biomass particle is heated at a rate below 20 °C/min from room temperature to the torrefaction temperature, which lies between 200 and 300 °C. Biomass residence time varies between 15 and 60 min after it has reached the torrefaction temperature. Fig. 2 illustrates the processes that occur in the biomass, which assumes that the residence time is such that the biomass fully transforms into char.

Depending on the particle size and heating rate, both drying and devolatilization processes may occur simultaneously inside the particle and thus one could expect wet biomass, dry biomass and char at the same time. This is observed in case of large particles within which large temperature gradients are present, but for very small particles such gradients are unlikely, and in such cases only one of these phases can be found inside the particle.

For each phase in Fig. 2, mass and energy balances were developed in order to follow its generation/destruction in each time step during the torrefaction process. These balances are associated with kinetic model, which describes the decomposition and generation