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Wood chips flow in a rotary kiln: Experiments and modeling

B. Colin, J.-L. Dirion*, P. Arlabosse, S. Salvador

Université de Toulouse, Mines Albi, CNRS UMR 5302, Centre RAPSODEE, Campus Jarlard, F-81013 ALBI Cedex 09, France

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ABSTRACT

Rotary kilns are well suited for processing woody biomass by torrefaction to produce bioenergy. One of the key issues for process design lies in the flow pattern modeling. The Saeman model is classically used to predict the mean residence time (MRT) and the bed depth profile of powder materials in rotary kilns. Its ability to describe wood chips flow arises. In the present study, residence time distribution (RTD) experiments are conducted with raw and torrefied wood chips. Effects of operating parameters – kiln slope, rotational speed and inlet flow-rate – on the average residence time, the variance and the mean solid hold-up are discussed. A plug flow with small extent of dispersion is emphasized, even if some segregation phenomena are highlighted. Torrefaction did not evidence any significant influence on the flow pattern. With a discrepancy of 20% between the measured and computed mean residence time, the predictive capacity of the classical Seaman model proved to be insufficient. The model is adapted to predict accurately the load profile and the mean residence time of particles with parallelepiped form. The discrepancy between experimental and calculated results is so reduced from 20% to 5% for the MRT and from 25% to 5% for the mean solid hold-up.

1. Introduction

Torrefaction of biomass is a thermal treatment under inert atmosphere at low temperature (250–300 °C). Due to the degradation of hemicelluloses – one of the biomass components – the torrefied products have new properties (Van der Stelt et al., 2011). For instance, they are more hydrophobic (Acharjee et al., 2011), more brittle (Bergman et al., 2004) and have a larger energy density than the raw biomass (Phanphanich & Mani, 2011). Several technologies have been identified to perform torrefaction (Sun et al., 2011), the most common being the fluidized beds (Atienza-Martínez et al., 2013), the fixed beds (Ratte et al., 2011), the multiple hearth furnaces (Batidzirai et al., 2013) and the rotary kilns (Mei et al., 2015). Among these reactors, the rotary kiln presents the advantage of being widespread in the industry for processing various materials, like minerals, coke, cement and various wastes (Li et al., 2002), in a wide range of temperatures. Indeed, rotary kilns are used at low temperature – below 200 °C – for drying (Shene & Bravo, 1998), but also at high temperatures – above 500 °C – for calcination (Mujumdar & Ranade, 2006). Consequently, the rotary kilns look like promising reactors to perform torrefaction.

The torrefaction yield is mainly governed by the temperature level and by the reaction's duration (Medic et al., 2012). In a rotary kiln, the movement of particles depends on the operating parameters. A majority of kilns operates in the rolling mode, which allows a good mixing of the bed (Boateng & Barr, 1996; Ding et al., 2002). The bed can be divided into two distinct parts: an active layer and a passive layer also called plug flow region. The active layer is the smaller one and is located at the free surface of the bed. It is formed by particles that roll from the top to the bottom of the inclined surface. There,

* Corresponding author. Tel.: +33 563493152; fax: +33 563493099.
E-mail addresses: baptiste.colin.2@gmail.com (B. Colin), dirion@enstimac.fr (J.-L. Dirion).
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Nomenclature

C	Tracer concentration ($g\,kg^{-1}$)
C_Q	Adjustment exponent applied to the volumetric flow rate (-)
C_α	Adjustment exponent applied to the inclination (-)
C_ω	Adjustment exponent applied to the rotational speed (-)
D	Internal diameter of the cylinder (m)
D_{ax}	Axial dispersion coefficient ($m^2\,s^{-1}$)
E	Exit-age distribution function (min^{-1})
E_P	Exit-age distribution function of the axial dispersion model (min^{-1})
E_T	Exit-age distribution function of the tanks-in-series model (min^{-1})
h	Local solid hold-up (%)
H	Mean solid hold-up (%)
J	Number of tanks in series (-)
L	Length of the kiln (m)
$m_{retained}$	Mass of wood chips retained in the cylinder (kg)
Pe	Peclet number (-)
Q	Mass flow-rate (kg/min)
$\dot{Q}_V^E$	Volumetric inlet flow-rate ($m^3\,s^{-1}$)
R	Radius of the cylinder (m)
t	Time (min)
$\bar{t}_s$	Mean residence time (min)
u	Mean axial velocity of particles along the kiln ($m\,min^{-1}$)
V_{cyl}	Volume of the rotary cylinder (m^3)
y	Local bed depth (m)
z	Axial position in the cylinder (m)

Greek letters

α	Inclination of the kiln (°)
β	Dynamic angle of repose (°)
θ	Central angle of sectional solid bed (°)
ρ	Bulk density ($kg\,m^{-3}$)
σ^2	Variance of the residence time distribution (min^2)
τ	Nominal space time (min)
ω	Rotational speed (rpm)

at the end of the rolling movement, particles enter the plug flow region that follows the movement of the wall of the kiln and brings particles at the free surface. As a consequence, the axial movement of particles occurs mainly when rolling in the active layer, due to gravity forces. These observations are the key to understand phenomena, such as segregation, but also to model heat and mass transfer. In addition to the temperature level, the mean residence time, the dispersion of the residence time distribution but also the solid hold-up have an influence on the thermal history of each particle in the rotary kiln. Therefore, characterizing the flow pattern and the solid hold-up are one of the main challenges for performing wood chips torrefaction in a rotary kiln.

Residence time distributions in rotary kilns have already been extensively characterized for granular packing of spherical and regular particles such as sand, powder, grains and so on (Sai et al., 1990). The model first established by Saeman (1951) provides the bed depth profile along the kiln and the solid hold-up, in addition to the mean residence time. This is of particular interest for modelling the whole process because it gives details about the transfer surfaces between the wall, the gas and the solid phases. This work has been further extended to several kiln configurations (Afacan & Masliyah, 1990), but always using sand as feeding material. Currently, the validity of this correlation for irregular particles shapes like wood chips has not been demonstrated. Indeed, these particles have a length-to-thickness ratio higher than 5 and the blend presents a very broad size distribution of particles.

In this study, residence time distributions (RTD) of both raw and torrefied wood chips in a rolling pilot-scale rotary kiln are measured and a method to evidence segregation phenomena is proposed. The influence of the rotational speed, the inclination and the solid inlet flow rate on the RTD curves of the raw biomass is discussed. Secondly, in order to investigate the influence of torrefaction on the flowing behavior of wood chips, results obtained with raw wood are compared with RTD experiments carried out with torrefied wood. Finally, a modified Saeman model describing accurately the bed depth profile along the kiln and the mean residence time of particles is developed and validated by comparison with experimental data.

2. Materials and methods

2.1. *Apparatus and materials*

A schematic representation of the pilot rotary kiln used in this study is proposed in Fig. 1. It consists of a cylinder of 4.2 m in length (L) and 0.21 m in internal diameter (D). The length-to-diameter ratio reaches 20, which is classical for drying or cooling processes (Kohav et al., 1995). The inner wall is covered by a metal grid to increase the roughness and establish the rolling mode. The inclination α can vary between 0° and 7° and the rotational speed ω between 1 and 21 rpm.

The biomass is introduced at the top end of the hopper and is transported with a vibrating conveyor to the entrance of the rotating cylinder. The hopper has a capacity of 10 kg of wood chips. The overall feeding system is continuously weighed. The inlet mass flow-rate of wood chips Q – varying from 0 to 10 kg/h – is regulated accurately (±50 g/h) by controlling the vibration amplitude of the conveyor. When processing in cold conditions – as for the flow study – the kiln end is opened and another weighing system is placed at the end of the cylinder to measure the outlet mass flow-rate. Steady state can thus be identified. On the contrary, for a torrefaction treatment, the kiln is hermetically closed and swept with nitrogen to provide an oxygen-free atmosphere. The cylinder is indirectly heated with an electrical furnace (electrical power 38 kW) from room temperature up to the set-point temperature.

Raw and torrefied beech wood chips are used in this study. The raw beech wood chips is provided by the French company SPPS. Characteristics of this material are summarized in Table 1. The torrefied biomass was produced in the pilot rotary kiln. The torrefaction was performed at 270 °C; the wood mass loss was 9.1 ± 2.7% on a dry basis (uncertainty is calculated for a 95% confidence level). As can be seen in Table 1, raw and torrefied particles have similar dimensions. Before the RTD experiments, both materials were stacked in contact with the ambient air, until the thermodynamical equilibrium was reached. Measurements of the dynamic angle of repose inside the rotating cylinder did not evidence any significant influence of the thermal treatment. Considering