Chemical Engineering Science 145 (2016) 80–89

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Experimental study on the axial mass transport of minced biomass (rape straw) into a pyrolysis rotating reactor working in the slipping regime

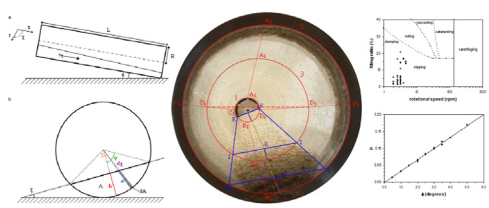
Francesco Desogus [a,*], Francesco Pili [b], Renzo Carta [a]

[a] Dipartimento di Ingegneria Meccanica, Chimica e dei Materiali, Università degli Studi di Cagliari, Piazza d'Armi, 09123 Cagliari, Italy
[b] Maim Engineering S.r.l., Piazza Giovanni XXIII, 09128 Cagliari, Italy

HIGHLIGHTS

- The dynamic behavior of a minced rape straw bed in the slipping regime is studied.
- A mathematical model of the process is developed.
- The main experimental information is obtained by image geometrical analysis.
- The bed profile is modeled and described through a parametric relationship.
- Some semi-empirical correlations for the axial advancing rate are proposed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 September 2015
Received in revised form
5 January 2016
Accepted 8 February 2016
Available online 12 February 2016

Keywords:
Dimensionless correlation
Minced biomass
Pyrolysis
Rape straw
Rotating reactor
Slipping regime

ABSTRACT

The paper presents an experimental study of the behavior of a minced biomass bed advancing into an inclined rotating drum to be used for biomass pyrolysis in the slipping regime. Minced rape straw was fed into the reactor with different feed rates, and its axial motion was examined at different slopes and cylinder rotating rates. By collecting and analysing images of the bed during the experimental runs, axial flow rates were determined; a mathematical model derived from mass and momentum balances was then applied, and the main parameter, the bed-wall friction factor, was obtained by regression of experimental data. Finally, in order to generalize bed dynamics, residence times and flow rates (mean values) were related to the experimental conditions by parametric semi-empirical and dimensionless correlations. Apart from its essential role in the future development of a whole chemical process model (including heat exchange, gas fluid dynamics, pyrolysis and gas phase reaction kinetics) to determine optimal working conditions, the dynamic model proposed here could also be of more general interest and be applied with other kinds of material and conditions on both an experimental and industrial scale.

1. Introduction

Rotating drums are commonly used in industrial applications such as mixing, drying, milling, coating, granulation/agglomeration, grinding (Yang et al., 2008), calcination (Liu et al., 2013), and in cement manufacture (Demagh et al., 2012). This kind of apparatus can be used to carry out pyrolysis, a process which has also

* Corresponding author. Tel.: +39 070 675 5079; fax: +39 070 675 5067.
E-mail address: f.desogus@dimcm.unica.it (F. Desogus).

http://dx.doi.org/10.1016/j.ces.2016.02.021
0009-2509/

proved promising in the treatment of solid wastes and which offers several advantages with respect to combustion and gasification: low dioxin and furan emissions, minor consumption of fossil fuels, wide flexibility in the kind of material to be processed (Descoins et al., 2005). Rotary reactors are commonly used to perform pyrolysis processes (Pedroza et al., 2014; Murugan and Gu, 2015), however, the need for flexibility and the wide range of operating possibilities require a complete understanding and description of all the phenomena occurring within the reaction environment (Descoins et al., 2005). Such an in-depth description can only be reached with a complete model that takes into account solid dynamics, heat transfer (from the walls to the solid and the gas phase, inside the solid bed, between the solid and gas phases), gas fluid dynamics and reactions (cracking, gas–solid, gas–gas) kinetics. The present work is focused on the solid phase motion, which was studied in conditions similar to those found in the process to be optimized, which is actually in operation in a pyrolysis pilot plant belonging to our partner, the Maim Engineering S.r.l. Company (Carta et al., 2012); these conditions were reproduced on a laboratory scale by means of a commercial rotating kiln apparatus.

It is known that the motion of granular solids inside partially filled rotating cylinders can happen with different kinds of regimes: depending on the rotation rate (ω) and on the cylinder radius (R), slipping, slumping, rolling, cascading cataracting, and centrifuging are possible regimes that can be achieved for increasing the rotational Froude number ($Fr=\omega^2R/g$, in which g is the acceleration of gravity) (Henein et al., 1983). Usually, incineration and pyrolysis processes are conducted in the slipping, slumping, and rolling regimes, characterized by low rotational rates (Li et al., 2002). The rolling regime is the most frequently used, particularly if high levels of mixing and heat transfer are requested (Fantozzi et al., 2007; Li et al., 2002; Liu et al., 2006). On the contrary, the slipping motion regime is characterized by negligible transverse rate components and axial dispersion: as a consequence, the bed can be studied as a rigid body that advances through the reactor, along which the thickness of the bed decreases as if in a plastic deformation. Little research has been dedicated to the slipping mode (particularly with respect to the rolling regime), on account of the very poor mixing which is an undesirable condition in many processes; on the contrary, this could be a necessary condition if the process to be performed requires sufficiently long residence times (considering that the axial advancing velocities are lower, operating in the slipping regime allows longer residence times with respect to the rolling one) and sufficiently slow heat transfer.

The need to follow the behavior of granular solids inside the drum and the impossibility of performing direct measurements induced some researchers to develop and apply non-invasive experimental techniques, such as Magnetic Resonance Imaging (Kawaguchi, 2010; Nakagawa et al., 1993; Hill et al., 1997), Positron Emission Particle Tracking (Parker et al., 1997; Ding et al., 2001; Ingram et al., 2005), fiber optics probes (Boateng and Barr, 1997), Particle Image Velocimetry and Particle Tracking Velocimetry (Alexander et al., 2002; Felix et al., 2002, 2007; Jain et al., 2002, 2004; Mellmann et al., 2004; Thomas, 2000), and Radioactive Particle Tracking (Alizadeh et al., 2013; Sheritt et al., 2003; Dubé et al., 2013); however, these techniques are often limited in the possible observations and are not always suitable in the case of ordinary and experimental processing (Huang et al., 2013); furthermore, most of the cited studies focused on spherical (or near spherical) particles, thereby limiting the possibilities of generalizations for real feedstocks (i.e. biomass), characterized by a non-regular shape, dimension, roughness, etc. Dubé et al. (2013); investigations about non-spherical particles are still few and limited to specific kinds of particles (Henein et al., 1983; Ingram et al., 2005; Boateng and Barr, 1997; Van Puyvelde et al., 2000; Woodle and Munro, 1993; Heinen et al., 1985).

Bearing in mind that our final purpose is to build a model to develop the processing of minced agricultural biomass waste in pyrolysis rotating reactors with a process characterized by low to medium temperatures (400–600 °C), low heating rates (to be exactly quantified), and long residence times (up to 1 h for solids) (Carta et al., 2012), the aim of this work is to present the motion behavior of biomass in the slipping regime and to provide a model description, which will allow our findings to be simply adapted to similar situations, starting from easily available information.

2. Material and methods

2.1. Experimental structure

The experimental apparatus used in this work is a commercial laboratory rotating furnace produced by Nabertherm® (rotary tube furnace for continuous processes, model RSR 120-750/11). The oven is equipped with a rotating quartz working tube made to rotate by a drive which can be adjusted (by a control switchgear) to between 1.33 and 30 rounds per minute. The material is introduced into the rotating chamber from a filling funnel by means of an electrically driven adjustable feed screw, and a blade system allows improved blending and a better conveyance of the charge in the tube. The quartz tube has a total length of 179 cm (163.5 cm excluding the zone occupied by the blade conveyor system) and an inner diameter of 10 cm (outer, 10.6 cm). At the end of the working tube the particles can be directly collected in a bottle. A digital display of the tilting angle of the tube makes it possible to regulate the slope by manually acting on a tilting mechanism (the inlet part is raised by two hydraulic pistons). The reactor is also equipped with a gas supply system (which can be connected to both the top and the bottom of the reactor) in such a way that operation can take place, depending on the specific needs, in air (still or moving), in protective or reactive gases or in a vacuum. The reaction chamber is provided with thermocouples and a three-zone PLC control for the optimization of temperature uniformity.

Measurements of mass flow rate were performed by an Ohaus® technical balance (Adventurer™ Pro AV 4102) provided with a USB interface for the continuous (at one second intervals) collection of weight data by a computer running the Ohaus® DAS (Data Acquisition Software) program.

2.2. Biomass

The material used in this study was rape (*B. napus L.* v. *oleifera*) straw, collected from a previous variety field trial (Lazzeri et al., 2009) built at the "Mauro Deidda" experimental farm (Dep. of Agriculture, University of Sassari, our research partner) in October 2007. This species has already been evaluated from an agronomic point of view in the Mediterranean environment (Deligios et al., 2013) and was carefully selected on the basis of outcomes provided by a previous paper (Cocco et al., 2014) which highlighted that the energy and environmental performances of an energy chain depend on the full exploitation of its biomass residues. Indeed, environmentally compatible bioenergy production can only be assessed by combining main crop yield with its by-products.

The raw material was minced by a shredder and sieved, giving rise to a biomass powder with 1.5 mm of granulometry. After this, the biomass was dried at 120 °C for 1 h in the rotating oven and then stored in sealed and airtight plastic containers to prevent rewetting from the atmosphere.