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Modeling and simulation of biomass drying in vortex chambers

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HIGHLIGHTS

- Modeling of biomass drying in vortex chambers using a non-stationary technique.
- Significant process intensification through high-G operation confirmed.
- Scale-up issues studied with the developed drying model.
- Product uniformity can be improved by compartmenting the vortex chamber.
- Air utilization can be optimized by re-usage in different vortex chambers/compartments.

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ABSTRACT

High-G fluidization in vortex chambers allows intensifying the drying of granular materials. The modeling, simulation and scale-up of vortex chamber based biomass dryers are addressed. Non-stationary experiments, batch for the biomass, are carried out to complement the data on continuous woody biomass drying in vortex chambers available in the literature. The drying models differ in the way they do or do not account for interfacial mass and heat transfer limitations, a non-uniform distribution of the moisture in the biomass particles and intra-particle diffusion limitations. Discrimination between the different proposed drying models and estimation of the model parameter(s) follows from simulations of both the continuous and batch experiments and regression. The retained biomass drying model is then used to study scale-up of the technology, focusing on continuous operation. Two major issues are addressed: (i) the product uniformity and (ii) the air consumption and utilization. Different vortex chamber configurations are simulated and analyzed: a single chamber or different chambers operated in parallel or in series (compartmented), allowing introducing a CSTR-in-series type behavior for the particles, combined with air feeding in parallel or in series over the different chambers.

1. Introduction

The use of pre-dried biomass allows improving the efficiency of biomass combustion, pyrolysis, or gasification processes. Drying the biomass prior to transportation is economically advantageous, but requires local, small and efficient drying units. Conventional biomass dryers are of rotating drum or fluidized bed type (Roos, 2008; Amos, 1998; Simpson, 1983; Mujumdar, 2007). Fluidized beds allow more efficient mass and heat transfer, but their performance is limited by (i) the bed density which decreases with increasing gas velocity, (ii) the non-uniformity of the particle bed with pronounced bubbling, and (iii) the gas-solid slip velocity which cannot exceed the terminal velocity of the particles in the earth gravitational field (Froment et al., 2010).

Rotating fluidized beds (RFBs) allow overcoming these limitations by operating high-G. In such reactors, the particle bed is rotating in a cylindrical chamber. The particles undergo a radially outward centrifugal force and a counteracting drag force by the gas flowing radially inward (Chen, 1987). Gas-solid slip velocities and related interfacial mass, heat and momentum transfer rates can be higher than in a conventional fluidized bed while maintaining a dense and more uniform particle bed (De Wilde and de Broqueville, 2009). RFBs are as such promising for the development of compact dryers of granular materials, in particular biomass.

RFBs make use of either a rotating chamber or a static vortex chamber. RFBs with a rotating chamber have been considered for the continuous drying of diced food materials (Hanni et al., 1976; Roberts et al., 1979) but industrial application is challenging because of sealing and vibrations issues. RFBs in a static geometry

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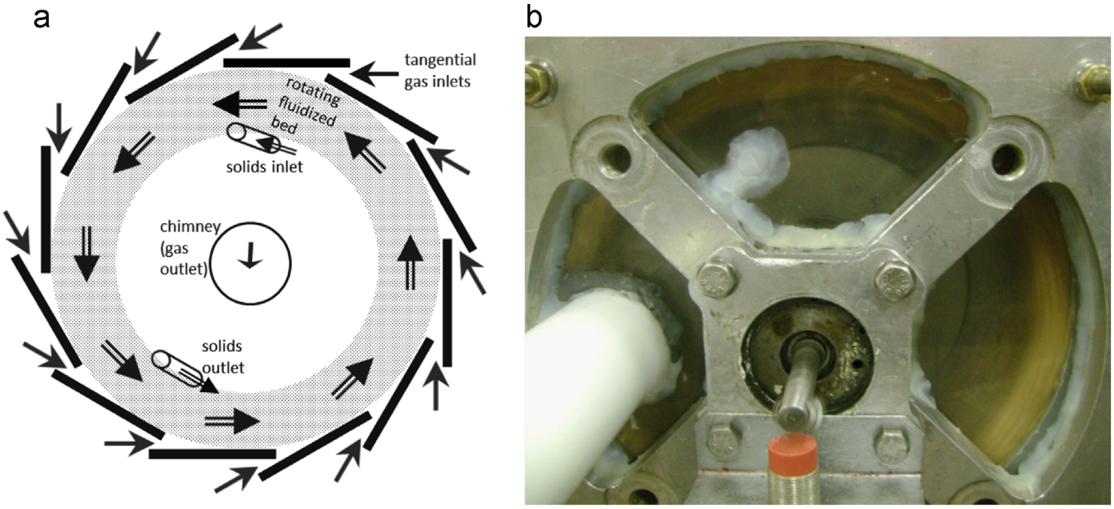

Fig. 1. (a) The use of a vortex chamber to generate a rotating fluidized bed in a static geometry (RFB-SG). (b) Picture of a rotating bed of biomass particles.

(RFB-SGs) make use of a vortex chamber. The particle bed rotational motion is generated by the tangential injection of the process gas through multiple gas inlet slots in the outer cylindrical wall (Fig. 1a). The gas is deflected radially inward upon contact with the particles and leaves through a centrally positioned chimney (De Wilde and de Broqueville, 2007). In vortex chambers, radial fluidization is not required as the bed is tangentially fluidized. In case the bed is radially fluidized, fast entrainment of particles into the chimney has to be avoided. This requires balancing the centrifugal force and the radial gas-solid drag force. Because both forces are impacted in a similar way by the gas flow rate, the vortex chamber has to be designed to ensure this balance for given particle characteristics. With a proper design, RFB-SGs then offer an increased flexibility with respect to the gas flow rate.

Drying of porous materials typically occurs in two distinct regimes. In the first "constant drying rate" regime, the drying rate is determined by interfacial heat and mass transfer. If the drying medium inlet temperature and humidity are constant, the particle moisture content (the liquid water contained in the particles) decreases linearly with time when drying batch-wise. At a given moisture content, intra-particle diffusion, that is, diffusion of vapor in the particle pores becomes limiting and the drying rate decreases. This is referred to as the "falling drying rate" regime. The moisture content at which the transition occurs depends on the structure of the particles, that is, its porosity and pore distribution, and the operating conditions (Mujumdar, 2007; Schlünder, 2004; Debaste et al., 2008). The increased bed density and improved bed uniformity allow process intensification in both the constant and falling drying rate regimes. Only in the constant drying rate regime, significant additional advantage is taken from the intensified interfacial mass and heat transfer.

Vortex chambers have been successfully used to remove the superficial moisture from various non-porous materials (Kochetov et al., 1969; Kochetov et al., 1969; Volchkov et al., 1993). More recently, Eliaers and De Wilde (Eliaers and De Wilde, 2013) reported experimental results on continuous (porous) biomass drying in a vortex chamber. In the present article, the modeling and simulation of biomass drying in vortex chambers are addressed and optimization and scale-up of the technology studied. Discrimination between different simulation models and estimation of the model parameters are carried out using experimental data of both previously reported continuous (Eliaers and De Wilde, 2013) and additional batch drying experiments using 2 different vortex chambers. Batch experiments offer many data points per experiment, a well-known advantage of non-stationary experimental techniques. Next, with the retained model, continuous operation at typical commercial scale is focused on and different vortex chamber designs (single or multi-chamber) and air feeding systems (uniform, co- and counter-current) are studied. Maximum product quality and uniformity and minimum air consumption are aimed at. A comparison with biomass drying in a conventional fluidized bed is also made.

2. Experimental set-up

Drying of 4 mm long, 4 mm diameter cylindrical beech wood particles with a density of 600 kg/m^3 on a dry basis is studied. To complement the continuous drying data of Eliaers and De Wilde (2013), non-stationary experiments, batch for the biomass, were carried out. Non-stationary data allow modeling with a sharply reduced number of experiments. In addition to the conventional fluidized bed and vortex chamber used by Eliaers and De Wilde (2013), a smaller-diameter vortex chamber with a different design was tested. The chamber design parameters and operating conditions are summarized in Table 1.

To build up a dense and uniform rotating particle bed in a vortex chamber (Fig. 1b), the centrifugal force generated by the air injection has to be maximized. The amount of tangential momentum injected for a given air flow rate can be increased by reducing the total inlet slot surface area, either by reducing the number of slots or their size. To guarantee a uniform air distribution, a minimum number of slots is, however, required. Another constraint is that the tangential momentum injected has to be transferred efficiently to the particle bed. With 4 mm sized biomass particles, this necessitates millimeter-sized slots. Tests using vortex chambers with smaller 0.2 and 0.5 mm gas inlet slots demonstrated inefficient momentum transfer to millimeter-sized particles. No stable bed could be obtained. The experimental procedure for the continuous experiments was described in Eliaers and De Wilde (2013). The procedure for the batch experiments is explained hereafter.

In the conventional fluidized bed, the air flow rate was 40 Nm^3/h, relatively low ($u_{sg} \cong 2 \times u_{mf}^{1G}$) to minimize bubbling. At time t_0, the pre-defined mass of humid biomass was introduced almost instantaneously in the fluidization column. The particle bed temperature was controlled through the air inlet temperature by means of a PID controller, but cannot be kept constant during a complete experiment due to the high initial drying rate. To characterize the drying process, the influence of the temperature on the drying rate has to be accounted for, requiring the coupled solution of the gas and solid