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Role of screen plate design in the performance of a rotor impact mill in fine grinding of biomass

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ABSTRACT

The role of rotor impact mill screen plate design in biomass grinding has attracted limited interest. This study aimed to clarify the effect of operational parameters and various screen designs on the fine grinding of *Sphagnum moss*. Contoured screens having forward (rasp) and backward (inverse rasp) inclined trapezoidal apertures of nominal sizes 0.2, 0.3, 0.4, and 0.5 mm were studied. A smooth screen plate having circular perforations (0.5 mm) was used as a reference. Flow phenomena were modeled with Computational Fluid Dynamics (CFD) using 2D geometry for the screen apertures.

Product particle size and capacity were mostly dependent on the equivalent diameter of the screen apertures together with rotor frequency and also on the screen design, while the aspect ratio was solely a function of particle size. Among the screens having nominal sizes of 0.3, 0.4, and 0.5 mm, the smooth screen produced the smallest particle size; followed by the rasp screens and the inverse rasp screens. The smooth screen had higher capacity than the rasp or inverse rasp screens, and a narrower operating range. In the case of 0.2 mm apertures, higher capacity was achieved with the inverse rasp than with the rasp screen. The net energy consumption (SEC) of grinding with the rasp screens was at a lower level than with the inverse rasp screens (or the smooth screen). No difference was seen in the case of the smallest size apertures, however.

The results, supported by CFD modeling, indicate that the incidence angle of particles does not explain the passage of particles through screen apertures. The passage is affected by the flow patterns above and within the apertures, and the pressure difference over the screen plate. The eddies within the apertures reduce their effective open area, resulting in product particles much smaller than the aperture size. When the aperture inclination is toward the tangential flow (rasp), an eddy is also generated in front of the aperture that turns the flow perpendicular to the screen surface within the aperture. In contrast, when the aperture inclination is against the tangential flow (inverse rasp), an eddy is generated above the aperture that guides the flow smoothly into the aperture, although the flow has to make a U-turn first. A design of inverse rasps seems to be beneficial when very small apertures are used, as it appears that the eddies formed above the apertures prevent blocking by dislodging accumulated particles. The low SEC with rasp screens does not seem to make the passage of particles through apertures easier, but it does enable more efficient size reduction because of the ability of rasps to serve as a grinding track.

1. Introduction

The emerging bioeconomy focuses the interest on the use of biomasses in a sustainable way. In biomass valorization, size reduction is usually a prerequisite. A fine size with a partially deconstructed cell wall and high specific surface are advantageous, e.g., in the conversion of biomass into fuels and chemicals (Cadoche and López, 1989; Jiang et al., 2017; Leu and Zhu, 2013), but also in applications where biomass is used in powder form as a functional filler, e.g., in biocomposites (Koivuranta et al., 2017; Stark and Rowlands, 2003). Extensive grinding, however, causes high electric energy consumption because grinding energy increases rapidly with reducing particle size. Due to its crucial role in biomass valorization, the energy consumption of lignocellulose size reduction has gained increasing research interest during recent years. A number of fine grinding studies on impact mills have been published for woody and herbaceous biomasses (Schell and Harwood, 1994; Naimi et al., 2013; Temmerman et al., 2013; Mani et al., 2004; Bitra et al., 2009; Yancey et al., 2013; Kobayashi et al., 2008; Gil et al., 2013; Karinkanta et al., 2012; Liu et al., 2016; Miao et al., 2010). Rotor impact mills are usually the first choice for size

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reduction, because they are compact, low-cost, robust, and product fineness can be controlled with integrated screens. The attainable particle size is limited, however, due to the blinding of the screen, leading to excessive material and heat build-up (Cadoche and López, 1989). Nevertheless, dry grinding of biomass with a rotor impact mill may be a potential pre-treatment method for nanoparticle or nanofiber production in order to reduce total energy consumption (Lee and Mani, 2017).

Particle breakage within rotor impact mills is a function of material properties, operation, and design parameters. Biomass material properties include structural and chemical compositions, which vary not only between plants but also within a plant. Moisture content can also be considered as a material property that has a great influence on the grindability of biomasses; the effect being directed to the bound water adsorbed into the cell wall. Material properties can be changed by thermal and chemical pretreatment such as drying, torrefaction (van der Stelt et al., 2011), steam explosion (Adapa et al., 2011), and acidic, alkali, or oxidizing treatment (Alvira et al., 2010; Tabil et al., 2011; Zhu et al., 2010). Operation and design parameters can be unified into a machine function (Vogel and Peukert, 2003) that determines the type of stress (being mostly impact (Grant and Kalman, 2002)), the intensity of stress (energy transferred to particles in a unit volume), and stress number (impacts per time in a unit volume). It has been suggested that the breakage of particles is primarily due to direct impacts between rotor elements and particles and secondarily due to impacts when particles collide onto the screen plate or static grinding elements e.g., a grinding track (Shi et al., 2003). Collisions between particles within the grinding zone are also expected but they are considered ineffective in respect of size reduction (Drögemeier and Leschonski, 1996). The intensity of stress is proportional to the rotor tip speed squared, while impacts per time are directly proportional to the rotor frequency (Austin, 2004). The cumulative impacts are determined by the residence time of particles within the grinding zone. Residence time is strongly dependent on the screen design, which affects the probability of particles passing through the screen plate. The passage of particles is governed by the size of apertures, open area, and airflow through the mill generated by the rotor or auxiliary fan. It has also been suggested that the incidence angle of particles entering screen apertures has an effect (Nied, 2007). The role of the screen plate design of rotor impact mills in capacity, product fineness, and energy consumption has attracted only limited interest in biomass grinding. Naturally, various sizes of apertures have been studied, but different aperture geometries have not been considered.

Special type screen plates, i.e., corrugated trapezoid screens (referred to hereafter as rasp screens, also known as Conidur screens) have been developed to avoid the problem of the blocking of small apertures in fine grinding (Nied, 2007). In rasp screens, apertures are essentially inclined toward the trajectories of fast moving particles on the screen surface. This results in an increased incidence angle that is believed to facilitate the passage of particles through the apertures. No studies have been found where rasp screens have been systematically investigated in the fine grinding of lignocellulosics. Neither is there any published data on the effect of operation and design parameters on size reduction, aspect ratio, and energy consumption in high-speed rotor impact milling of lignocellulose materials with the aforementioned screen designs.

This study aims to clarify the effect of operational and screen design parameters on energy consumption, size reduction, and aspect ratio in the fine grinding of *Sphagnum moss* with a rotor impact mill equipped with a screen classifier. The *Sphagnum moss* chosen for the study is an interesting non-wood lignocellulose biomaterial because of its abundance and productivity. Another aim is to provide comparable data in order to understand how the operating and design parameters affect the results. This may help when selecting proper grinding conditions for the efficient size reduction of biomasses. In order to understand the effect of screen design and aperture geometry, flow phenomena above and within the screen aperture were modeled by Computational Fluid Dynamics (CFD).

2. Materials and methods

2.1. Sphagnum moss

Sphagnum moss (more information is given in Supplementary Information) harvested on the surface layer of peatland was used as the lignocellulose material. Based on von Post's 10-scale classification of humification (H1-H10) for peat (Andriesse, 1988), the moss sample was classified as H2, i.e., it was slightly decomposed. The moss raw material provided by Vapo Oy (Finland) has a moisture content of about 34%. The material was homogenized by pre-grinding with a Rapid 40 knife mill having a screen plate with 4 mm perforations. The median particle size was of the order of 1 mm. After drying the moss to an average moisture mass fraction of 3% (varied between 2–6%) at a temperature of 60 °C for 48 h, the *Sphagnum moss* was fine ground.

The moss chemical composition was determined as follows (analysis method/standard in parenthesis): cellulose content 20% (Kürchner-Hoffner method (Reid and Lynch, 1937); dilute NaOH solubility 55% (Tappi T212); Klason lignin 21% (Tappi T222); acetone soluble extractives 4.3% (Tappi T280); ash at 525 °C 1.3% (TAPPI T211).

2.2. Analyses

The particle volumetric size distribution was measured with a laser diffraction analyzer (Beckman Coulter LS 13320, Miami, FL, USA). The maximum size of this technique is limited to 2 mm. Because of the 'large-end cut', the feed particle size could not be measured reliably but there was no problem with the fine ground powders.

The size distribution was characterized by its width, i.e., span:

$$span = (d_{90} - d_{10})/d_{50} \quad (1)$$

where d_{90} is the 90% undersize limit
d_{10} is the 10% undersize limit
d_{50} is the median particle size

The aspect ratios were calculated from optical images obtained with a CCD camera from the tube flow of the diluted powder samples. Images were recorded in a cuvette having a rectangular cross section. The average aspect ratio of a sample was calculated by dividing the average length of the particles by the average width of the particles. Three parallel analyses having at least 50 000 particles each were analyzed for the aspect ratio calculations.

2.3. Fine grinding of moss

The pre-ground samples were divided into subsamples and fine-ground with an Alpine Ultraplex UPZ100 (Hosokawa Alpine) rotor impact mill (Fig. 1 left). Grinding was performed using various screen designs: with contoured rasp screens (Fig. 1, right) having trapezoidal apertures of a nominal aperture size of 0.2, 0.3, 0.4, and 0.5 mm, and with a smooth perforated screen with circular holes of 0.5 mm in diameter. The rasp screens of 0.2 and 0.5 mm were also tested with the inverse direction of rotation. The actual dimensions (height, area) of the rasp screens were measured from photographs and are presented in Table 1. Equivalent diameters in Table 1 refer to the diameter of

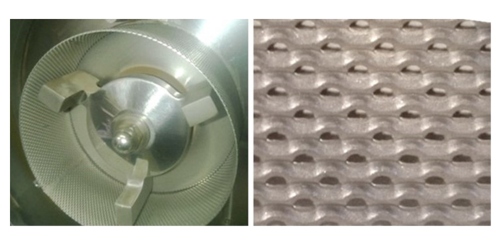

Fig. 1. UPZ100 rotor and circumferential screen having a diameter of 105 mm and width of 50 mm (left) and a rasp screen with contoured surface and trapezoidal apertures (right).