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2 Dimensional finite stochastic breakup model of biomass particle breakup

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HIGHLIGHTS

- ▶ We proposed a new model based on the anisotropy of biomass material in spatial structure.
- ▶ This model provides a proper description about the breakup of biomass material.
- ▶ This model could predict the change of biomass particles shape with the decrease of size.

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ABSTRACT

Due to the high content of cellulose, hemicellulose and lignin, the anisotropy of biomass particle in spatial structure induces the difference of mechanical properties in different directions. In this paper, based on the finite stochastic breakup model and anisotropy of biomass particles, 2-dimensional finite stochastic breakup model (2D-FSBM) of biomass particle was proposed, and the breakup process of biomass particle was investigated. In this model, the strength difference in different directions and the minimum mass ratio of a sub-particle to the parent particle were both considered. The simulation results agreed well with the experimental results in particle shapes, which indicated that 2D-FSBM could predict the breakup process of biomass particles.

1. Introduction

Biomass feedstock destined for the conversion to fuel and other chemicals usually need to be ground to a certain particle size (Asadullah et al., 2002; Demirbas, 2005; McKendry, 2002; Rapagna et al., 1998). However, because of the distribution of cellulose, hemicellulose and lignin in biomass is anisotropic, particles with different mechanical properties are generated.

Kolmogorov (1941) proposed a stochastic theory for the breakup of solid particles that describe the cascade of uncorrelated breakage events. The breakup of solid particles was considered a random discrete process where the probability of breaking each parent particle into a given number of sub-particles was independent of the size of the parent particle. This theory was gradually applied to such processes as rock crushing and breakage of droplets. Based on Kolmogorov's theory, Cheng and Redner (1988) developed a scaling theory for linear fragmentation processes. Ben-Naim and Krapivsky (2000) investigated fragmentation processes with a steady input of fragments, solved for the full time-dependent behavior in terms of the input function, and found that the size distribution exhibits a universal scaling behavior in the long time limit. In addition, other researchers (Ernst and Szamel, 1993; Huang et al., 1996; Treat, 1997) described Kolmogorov's discrete stochastic process with mathematical models that were based on analytic solutions of the evolution of the kinetic equation. In these models, the particle size distribution evolves continuously with time instead of with the growing number of breakup events in discrete models. Apte et al. (2003) and Gorokhovski and Saveliev (2003) extended Kolmogorov's stochastic theory to the field of liquid spray. Zhou et al. (2000) proposed a stochastic breakup model for droplets and, based on Zhou's model, Gong et al. (2005) and Liu et al. (2006) developed the finite stochastic breakup model (FSBM).

However, these models are one-dimensional models, in which particles or droplets are considered as isotropic, hence breakup direction was not considered. In the present paper, a two-dimensional finite stochastic breakup model (2D-FSBM) is proposed based on the anisotropy in spatial structure of biomass particles to investigate the breakup process of biomass particles by a numerical simulation. The parameters of the model were confirmed with experiments.

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Nomenclatures

A	area bearing the force (m^2)
a	aspect ratio of biomass particle (1)
c	ratio of material strength in two directions (1)
d	thickness of the blade (m)
L	effective breakup distance (mm)
m	minimum mass ratio of a sub-particle to the parent particle (1)
m_X	minimum mass ratio of a sub-particle to the parent particle in horizontal direction (1)
m_Y	minimum mass ratio of a sub-particle to the parent particle in vertical direction (1)
E	consumed energy during the breakup process (J)
E_X	consumed energy during the breakup process in the horizontal direction (J)
E_Y	consumed energy during breakup the process in the vertical direction (J)
E_i	imported energy during particle breakup (J)
K	probability ratio of particle breakup of one particle in two directions (1)
P	particle breakup probability (1)
P_Y	breakup probabilities in vertical direction (1)
x	width of biomass particle (mm)
x_0	initial width of biomass particle (mm)
x_c	final average particle width (mm)
y	length of biomass particle (mm)
y_0	initial length of biomass particle (mm)

Greek Symbols

σ	material strength ($N\,m^{-2}$)
σ_X	material strength in horizontal direction ($N\,m^{-2}$)
σ_Y	material strength in vertical direction ($N\,m^{-2}$)

2. Model development and experiments

2.1. The 2D-FSBM of biomass particle breakup

2.1.1. The assumptions of 2D-FSBM

The basic principles of the 2D-FSBM are:

(1) The shape of biomass particle is considered as a cuboid with a width and thickness of x and a length of y.
(2) The breakup of one biomass particle occurs in two directions: horizontal and vertical, as shown in Fig. 1a. The *horizontal* direction is perpendicular and *vertical* direction is parallel to the grains. The probability ratio of particle breakup in two directions K is determined by the aspect ratio of particle a ($a = y/x$) and the ratio of material strength c ($c = \sigma_X/\sigma_Y$, where σ_X and σ_Y are the material strength of horizontal and vertical directions, respectively).
(3) When a particle touches the blade, it will break up into several sub-particles and the mass ratio of a sub-particle to the parent particle is a random variable in the closed interval [m, $1-m$] with a uniform probability distribution where m is the minimum mass ratio of a sub-particle to the parent particle, $0 < m < 0.5$.
(4) Owing to the needle-like shape of the biomass, the contact of particles with a blade mainly occurs along the longitudinal direction. The breakup in the vertical direction (which produces the sub-particles with a minor width) would be concomitant, which is mainly induced by the transferred energy along the grinds.
(5) The breakup of a biomass particle will stop when the average width of the particles is smaller than the experimental result x_c.

2.1.2. Parameters in 2D-FSBM

Before the 2D-FSBM is employed to investigate the breakup process of biomass particle, the initial particle sizes x_0 and y_0, the final average particle width x_c, the minimum mass ratio of a sub-particle to the parent particle m, the ratio of material strength in two directions c, the particle breakup probability P and the probability ratio of one particle in two directions K need to be determined.

The size of one biomass particle is described by the values x and y which can be known easily considering the two-dimensional nature of the model. x_c was used as the convergent condition which means that the breakup process will stop when the average width of particles is smaller than x_c. *Width* is taken as the basic dimension since a biomass particle passes a sieve pore more easily in the direction of width than length. The minimum mass ratio of a sub-particle to the parent particle, m, indicates the particle breakup position, which means that sub-particle smaller than the minimum particle would not appear during the breakup. The ratio of material strength in two directions, c, mainly describes the strength difference in two directions to reflect the anisotropy of biomass particle. The particle breakup probability P determines whether the particle will break up. The parameter K is the probability ratio of one particle in two directions and decides the breakup directions when one biomass particle breaks up.

The related parameters of the 2D-FSBM were determined as follows. The initial particle size x_0, y_0 and the final average particle width x_c were obtained from experiments by statistics method. The minimum mass ratio of a sub-particle to the parent particle m and the ratio of material strength in two directions c were obtained from the simulation results.

Due to the high content of cellulose, hemicellulose and lignin in biomass, the material strengths perpendicular (horizontal direction) and parallel to grain (vertical direction) are different. Thus the shape of biomass particle is needle-like. In this model, the particle breakup probability P is mainly determined by the contact of particle and blade that mainly occurs in the length direction due to the needle-like shape. So P is determined according to the following simple assumption. As shown in Fig. 2, L is defined as the only effective breakup distance in which the biomass particle can break up. Therefore, P is expressed as follows:

$$P = \begin{cases} 1, & y \geqslant \frac{L}{2} \\ y/(L-y), & y < \frac{L}{2} \end{cases}, \tag{1}$$

in which y is the length of biomass particle, and L is the parameter reflecting the pulverizer characteristics. L was difficult to determine in the experiment because it could not be measured in an actual breakup process, but a good result was attained in the simulation for all kinds of biomass if $L = 4$ mm.

According to the assumptions, the breakup of a biomass particle would result in different sub-particles (Figs. 1b). As shown in Fig. 1b, one parent particle would produce two or four sub-particles, depending on the ratio of imported energy E_i to breakup energy in the vertical direction E_Y.

The definition of material strength is expressed as

$$\sigma = \frac{N}{A}, \tag{2}$$