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Batch grinding kinetics of scrap tire rubber particles in a fluidized-bed jet mill

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ABSTRACT

Grinding plays an important role in achieving scrap tires recycling. The batch grinding kinetics of scrap tire rubber particles in a fluidized-bed jet mill was studied based on population balance modeling. The selection and breakage functions were obtained according to the first Kapur function. It is found that these two functions were affected by the operating parameters such as the inlet gas pressure, feed load and grinding temperature. The breakage behaviors of scrap tire rubber particles under different operating conditions in the jet mill were discussed. Furthermore, a cubic function was proposed to predict the relation between the Kapur function and the particle size. The model prediction agrees well with the experimental data obtained under various operational conditions.

1. Introduction

The global automotive tire yield maintains a continuous growth in recent years. Nearly 1000 million tires annually reach the end of their useful lives, and by the year 2030, the number of tires from motor vehicles is likely to reach 1200 million [1]. Conventional methods, such as burning or burying waste tire underground, emit greenhouse gases like CO_x and NO_x and other poisonous substances [2–4]. It may increase environmental risks and pose a potential threat to human health. Therefore, to avoid the secondary pollution is a meaningful and challenging topic in realizing the recycling of the waster tire rubber.

Recently, recycling waste tire rubber by powder technologies is widely considered as a promising recycling method [5–9]. The ground scrap tire rubber is defined as the rubber that is reduced to a particle size of 9.51 mm or less. It can be used as modifiers to asphalt paving mixtures and an additive to cement concrete, or it can also be used as raw materials in the manufacturing of new high value-added products, such as printing ink and paint if the rubber particle size <0.074 mm. Recycling scrap tire rubber by powder technologies can not only benefit the environmental protection, but furthermore, rubber powder can cut down the expenses efficiently and improve the performance of the products significantly [10–12]. The particle size requirements of the ground scrap tire rubber depend on the end user, and the prices of the ground scrap tire rubber are usually inversely proportional to the particle size of the product. It is important to predict the particle size distribution and understand the breakage mechanism in the waste tire rubber grinding process. Fluidized-bed jet mills have been widely applied in many industries which can provide ambient and cryogenic grinding. They offer various advantages such as high degree of fragmentation with a narrow size distribution, low wear, low noise, and their ability to grind heat sensitive materials [13–14]. Hence, fluidized-bed jet mills are important tools to produce fine particles of scrap tire rubber by ambient or cryogenic grinding. However, it should be noted that the published literature is mainly concerned with the grinding behavior of brittle materials [15–17], but very little has been carried out on the kinetics of batching grinding of polymeric materials like tire rubber under various operational processes in a fluidized-bed jet mill.

The objective of this study is to investigate the batch grinding kinetics of scrap tire rubber particles in a fluidized-bed jet mill under various operating parameters (such as inlet air pressure, feed load and grinding temperature) by population balance modeling based on Kapur's simplification of the batch grinding equation.

2. Theoretical

The population balance model is often used for design, simulation, control and optimization of the grinding process. Based on the population balances, Reid [18] gave the batch grinding equation by means of

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dividing a particle size distribution into several classes indexed from 1 (coarse) to n (fine) as follows:

$$\frac{dw_i}{dt} = -S_i w_i + \sum_{j=1}^{i-1} b_{ij} S_j w_j \ \text{ with } \sum_{i=j+1}^{n} b_{ij} = 1 \ \text{ and } \ n \geq i \geq j \geq 1 \qquad (1)$$

where i and j are specific size classes, n is the total number of size classes, w_i is the mass fraction of particles in class i, t is the grinding time, S_i is the selection function defined as the probability of breakage of particles in class i and b_{ij} is the breakage function defined as the mass fraction of particles of class j which are found in class i after a short instant of grinding.

If assuming the selection function and breakage function to be time-independent, the analytical solution of Eq. (1) can be given in cumulative form as

$$R_i(t) = \sum_{j=1}^{i} \left(\sum_{k=j}^{i} \tau_{kj} \right) \exp(-S_j t) \qquad (2)$$

where $R_i(t)$ is the cumulative oversize mass fraction at time t and τ_{kj} is the transfer parameter which is calculated from the selection and breakage functions [19].

It is difficult to obtain the selection and breakage functions experimentally, especially in case of fine particles [13]. Although optimization techniques can be used, this type of solution is very unstable as Eq. (2) is a sum of exponentials [20]. Kapur [21–22] provided an effective way to obtain the approximation of Eq. (1) and the cumulative oversize mass fraction $R_i(t)$ can be expressed as

$$R_i(t) = R_i(0) \exp\left[K_i^{(1)} t + K_i^{(2)} \frac{t^2}{2} \right] \qquad (3)$$

where $K_i^{(1)}$and $K_i^{(2)}$are the so-called Kapur functions which can be obtained by use of selection and breakage functions [22]. Berthiaux and Varinot [13] further pointed out that it is sufficient to describe the particle size evolution by the single term $K_i^{(1)}$ for short grind times. This gives

$$R_i(t) \approx R_i(0) \exp\left(K_i^{(1)} t \right) \qquad (4)$$

The first Kapur function $K_i^{(1)}$ can be calculated by linear fitting from batch grinding data. Then, the selection and breakage functions can be calculated by a series of matrix transforms [19]

$$S_i = -K_i^{(1)} \qquad (5)$$

$$b_{i,j} = -\frac{K_{i-1}^{(1)} - K_i^{(1)}}{K_j^{(1)}} \qquad (6)$$

3. Material and methods

3.1. Raw material

Fig. 1 shows the initial particle size distribution of the scrap tire rubber particles used in the grinding experiments. The rubber particles with d_{50} of 330 μm and d_{90} of 725 μm were purchased from Shandong Shenglongtai Polymer Co. Ltd., China. Fig. 2 shows the thermal analysis of rubber powder. The composition of rubber powder was determined by Thermogravimetry and Differential Thermal Analysis (TG-DTA) under nitrogen flow (Fig. 2(a)). A mass loss of 53% was observed in TG from 300 °C to 475 °C due to the degradation of the polymer and the rest is carbon black and additives. The differential scanning calorimetry curve of rubber particles as shown in Fig. 2(b) indicates that a glass transition took place at −61 °C.

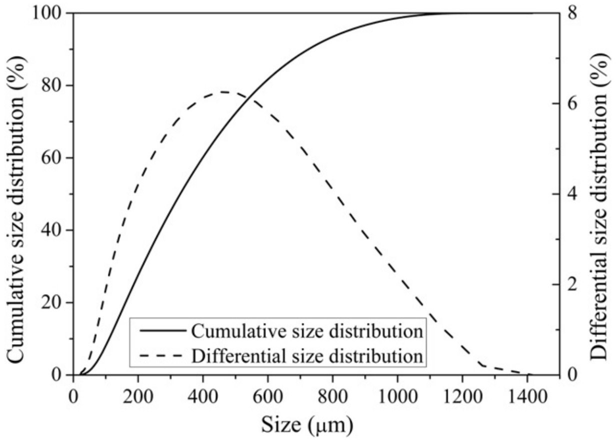

Fig. 1. Particle size distribution of scrap tire rubber particles.

The particle size distribution was measured by Malvern Mastersizer 2000 particle size analyzer (UK). TG-DTA was performed in a nitrogen atmosphere with a Setaram Setsys 16/18 thermogravimetric analyzer (France). The glass-transition temperature was characterized in the range of −100 °C to 40 °C, with a heating rate of 10 °C·min^{-1}, in nitrogen by a TA Q2000 differential scanning calorimetry (US).

3.2. Experimental setup

The schematic diagram of the experimental setup is shown in Fig. 3. The system mainly consists of jet mill, oscillating feeder, compressor, self-pressurized cryogenic liquid nitrogen container, cyclone separator, dust remover and induced fan. Table 1 lists the technical data of the jet mill. The grinding chamber of the jet mill is cylindrical with a conical bottom. Four grinding nozzles are mounted horizontally at 90° in the bottom of the jet mill. The compressed gas is accelerated through the nozzles at extremely high velocities and the feed material in the grinding chamber is accelerated by the gas. Particles are draw into the accelerated gas streams and are ground via inter-particle collisions in the jet stream. The compressor and self-pressurized cryogenic liquid nitrogen container are used to provide the compressed gas for ambient and cryogenic grinding of tire rubber particles. The gas temperature in the chamber is measured by a thermocouple and controlled by adjusting the liquid nitrogen inflow rate. The gas pressure in the buffer tank is measured by a pressure gauge and it is considered as inlet air pressure.

3.3. Batch grinding experiments

To perform batch grinding experiments, the tested particles were inserted into the grinding chamber simultaneously through the feeding channel. In the cryogenic grinding, the test particles were precooled to −80 °C first. The feed inlet was closed after the feeding because in the experiments we found that the particles could escape from the chamber through the feeding channel when inlet air pressure reached 0.8 MPa. The vertical air classifier on the top region of the grinding chamber was operated at its maximum rotating speed of 3000 rpm to limits the fines leaving the chamber. These operations may be considered to approach the batch grinding condition because only a small quantity of very fine particles escape from the chamber in the short duration of the experiment which would not play an important role in the batch grinding process. After grinding at each time interval (1, 2, 3, 4 and 5 min), the products under a certain operational condition gathered from the grinding chamber and the product collecting pot were mixed together for particles size analysis. The experimental conditions are listed in Table 2. Although the inlet air pressure is the same for Test 1