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Application of Relative Regional Total Energy in Rotary Drums with Axial Segregation Characteristics

Qiuhua Miao, Peng Huang, Yifei Ding

Abstract**—**Particles with different properties tend to be unevenly distributed along an axial direction of the rotating drum, which is usually ignored. Therefore, it is important to study the relationship between axial segregation characteristics and particle crushing efficiency in longer drums. In this paper, a relative area total energy (RRTE) index is proposed, which aims to evaluate the overall crushing energy distribution characteristics. Based on numerical simulation verification, the proposed RRTE index can reflect the overall grinding effect more comprehensively, clearly representing crushing energy distribution in different drum areas. Furthermore, the proposed method is applied to the relation between axial segregation and crushing energy in drums. Compared with the radial section, the collision loss energy of the axial section can better reflect the overall crushing effect in long drums. The axial segregation characteristics directly affect the total energy distribution between medium and abrasive, reducing overall crushing efficiency. Therefore, the axial segregation characteristics should be avoided as much as possible in the crushing of the long rotary drum.

Keywords**—**Relative regional total energy, crushing energy, axial segregation characteristics, rotary drum.

I. Introduction

SINCE the advent of rotary drum equipment such as ball mill, the work efficiency problem has not been able to obtain an important breakthrough. Therefore, how to improve crushing and grinding efficiency to reduce energy consumption is a hot research topic [1]. In recent years, with the rapid development of various particle simulation technologies, researches on the grinding efficiency of rotary drums have also emerged one after another, mainly including the influence of power and torque [2], particle velocity field and impact energy [3], drum size and speed [4], [5], steel ball size and shape [6]-[8], lifting bar structure [4], [9] and other parameters. However, many researches have shown that the axial mixing and segregation behavior occurs simultaneously during the grinding process of the rotary drums, but almost all of them are based on the assumption that the media particles are uniformly distributed, ignoring movement and segregation behavior of different types of particles in the axial direction of the drum [10], [11]. When the axial segregation behavior of binary media exists, the media and abrasive particles in the rotating drum are not uniformly distributed along the axial direction. This means that the number of particles with the same size will fluctuate along the axis of the drum, causing media of different sizes to gradually aggregate and eventually form the alternating axial segregation bands. Therefore, the assumption of uniform grinding effect in all region of the drum is not suitable for the grinding situation of the long drum.

Although the research on particle mixing and segregation phenomenon has received widespread attention, previous efforts only studied the radial mixing and segregation behavior of particles in 2D planes or shorter drums, ignoring the phenomenon of mixing and segregation in long drums [12]-[15]. In recent years, the axial segregation phenomenon has gradually attracted the interest of many researchers, such as related research focused on influence factors of axial segregation characteristics [12], end-covers [16], [17], drum lifting bars [11] and other parameters. Although the understanding of the axial segregation behavior of particles in the rotary drum is also increasing, most researches only qualitatively analyze the influencing factors and characteristic patterns of the axial segregation behavior, without substantial quantitative analysis. Therefore, there is still a lack of research to evaluate the relationship between axial segregation characteristics and crushing energy [18]-[20].

In the study of the working performance of the ball mill, Cleary [11] simulated a two-chamber cement ball mill with a diameter of 4 m based on the Discrete Element Method (DEM), and analyzed in detail the axial particle segregation process and collision energy utilization. It was found that changing the shape of the liner will cause the particles to move in the axial direction. Morrison and Cleary [21] studied the collision energy of the media and material particles in the rotary drums through simulation. According to the relationship between the collision frequency and the collision loss energy, it is not difficult to find that the number of low-energy collisions in the grinding process of the ball mill accounted for the majority, whereas the high-energy collisions accounted for the minority. Similarly, Wang et al. [5] established a rotary drum model through DEM, using two kinds of particles to represent the grinding ball and the abrasive respectively, and studied the three energy forms inside the rotary drum, namely: collision energy, dissipation energy, and maximum impact energy. In addition, the combination of energy information and Population Balance Model (PBM) can well predict the change rule of product size. Considering the axial segregation phenomenon of the rotary drum, in our previous study, we proposed a method of total regional energy to evaluate the grinding efficiency of each part of long drum

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[22]. Compared to traditional evaluation indicators (such as average kinetic energy and number of collisions), the regional total energy indicator reflects grinding energy of different regions in the drum, and can more accurately reflect the grinding condition in the drum. It is a pity that the absolute regional total energy cannot reflect the energy loss of a single particle under various working conditions, which makes it difficult to compare each group horizontally.

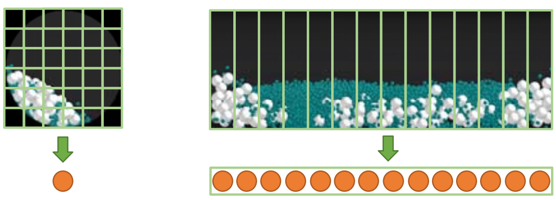
Despite a great deal of research has been done on the particle crushing energy inside the rotary drum, it is a more realistic and challenging situation when axial segregation characteristics arise in long drums. Therefore, this work proposes a RRTE index, which is suitable for evaluating particle collision energy in a long drum. Furthermore, we use the proposed index to study the relationship between crushing efficiency and axial segregation characteristics of binary particles in long drums.

The rest of this article is structured as follows. In Section II, the corresponding DEM model is determined and verified by experiments. Section II details our proposed RRTE index. In Section IV, the radial and axial mixing-segregation behavior in the drum is studied, and the relationship between the axial segregation characteristics and the overall crushing energy is qualitatively and quantitatively analyzed. Finally, Section V concludes the article.

II. Evaluation Index

A. Axial Center Nearest Neighbor Index

In the quantification research on mixing-segregation degree, the Lacey index evaluation method usually quantifies the radial segregation degree [23]. On this basis, we proposed a quantitative index for axial segregation, the axial center nearest neighbor index (ACNN), in previous studies [19], [24]. This index mainly regards each radial section as a unit and defines the segregation distance of particles in the axial direction of the drum, which is used to quantify the segregation degree of particulate matter in the axial direction [19], [24]. The ACNN method uses all type particle information in the sample grid to quantify the degree of mixing and segregation. Fig. 1 shows the derivation process of the ACNN evaluation method.



(a) (b)

Fig. 1 The derivation process of the ACNN method: (a) Simplified radial section, (b) Simplified axial section

As shown in Fig. 1, we first obtain the segregation index for each radial section in the simulation area and the weight of the particles in the drum. Then, according to the axial center compensation distance of the radial section, the segregation index SI of the particles in the drum is calculated as:

$$SI = \frac{L_{max} - L_{now}}{L_{max} - L_{min}} \quad (1)$$

where the value of segregation index in (1) ranges from 0 to 1. Among them, $SI = 1$ means completely segregated state, while $SI = 0$ means completely mixed state. In addition, L_{now} is the actual axial nearest neighbor segregation distance of the particles. L_{min} and L_{max} are the axial segregation distance when completely mixed and fully segregated, respectively.

B. Relative Regional Total Energy Index

In the research on particle crushing energy, it is usually based on the following assumption: the crushing effect of mineral materials is positively related to the energy loss during the collision. That is, the more energy is lost during the collision, the more energy is used for cushion [25], [26]. However, the rotary drums under different working conditions often have different amounts of media and materials. The absolute regional total energy cannot reflect the energy loss relative to a single particle under various working conditions, which makes it impossible to be used for mutual comparison of each group [22].

To facilitate transverse comparison of crushing performance of rotary drums under different working conditions, this paper introduces the Relative Regional Total Energy (RRTE) index to better adapt to the two angles of radial and axial section. This method calculates the total number of related objects in each region (the sum of the number of media and abrasives particles), and then divides the total energy of the region by the total number of related objects to get the RRTE. The specific application is as follows:

First, in the meshing stage, the rotating drum is uniformly meshed in the axial and radial directions along the axial and radial directions of the computational domain, and $N \times N \times N'$ meshing is performed here. The diameters of the media particles are d_1 and d_2, and the inner diameter and length of the drum are D and L, respectively. The mesh size is usually 1.5 - 2 times the size of the larger media particles. The number of meshing regions in the two dimensions of the radial section is N, and the number of meshing regions in the axial section is $N' = L \cdot N / D$. For the region（i，j，z）, the number of collision states at time t is S, and the energy loss in a single collision is e, the following relationship is satisfied:

$$e \sim \Theta(E_{\min}, E_{\max}) \quad (2)$$

where $E_{\min}$ and $E_{\max}$ are the minimum and maximum loss energy of collision in this region, respectively. And Θ is the distribution function, which is related to the number of particles, the drum speed and other parameters. Then, the number of collisions in each region and the energy loss of each collision can be counted respectively, and finally the total energy loss $E_{i,j,z}$ of each region can be calculated as:

$$E_{i,j,z} = \sum_{k=1}^{S} e_k \quad (3)$$

where e_k is obtained by sampling from the distribution. And $E_{i,j,z}$ is the total energy of the region (i, j, z), which reflects the total energy loss in the region.

When evaluating the RRTE of the radial section, the Monte Carlo method is used to sample the energy loss of each collision to simplify the calculation. And then we calculate the total number of collisions in the region of the respective energy distributions, sampling and energy distribution. On this basis, the total energy of each collision region is calculated according to (4). Finally, the RRTE of each meshing region is superimposed on the radial section along axial direction of the drum, as shown in Fig. 2.

$$E_{i,j} = \frac{1}{N_t N_{\Delta t}} \sum_{n=1}^{N_{\Delta t}} \sum_{z=1}^{N'} E_{i,j,z} \tag{4}$$

where $N_{\Delta t}$ is the total number of time steps in the collected grinding process, and N_t is the total number of related objects in each group. Similarly, when evaluating the axial section, the RRTE of each region is superimposed on the axial section along the radial direction, as shown in Fig. 3. The calculation formula is:

$$E_{i,z} = \frac{1}{N_t N_{\Delta t}} \sum_{n=1}^{N_{\Delta t}} \sum_{j=1}^{N} E_{i,j,z} \tag{5}$$

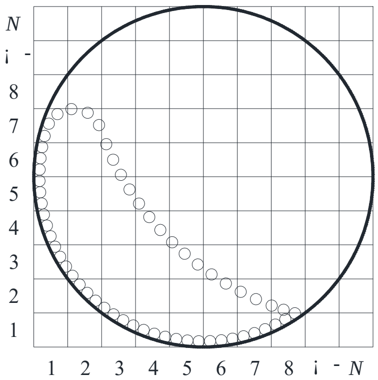


Fig. 2 Radial section area division diagram

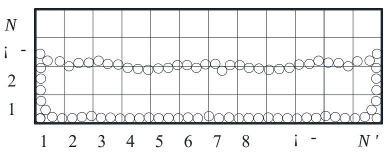


Fig. 3 Axial section area division diagram

The above-mentioned RRTE (media-abrasive) index will be used to evaluate the grinding efficiency, to further study the influence of the axial segregation distribution characteristics on the grinding efficiency of the rotary drum.

III. DEM Model and Experiments

A. DEM Model

The simulation in this paper is based on the model proposed by Cundall and Strack in 1971, namely the Discrete Element Method (DEM) [27]. It is helpful to understand the relationship between the microscopic and macroscopic properties of discrete particulate matter based on establishing constitutive relationship between particle contact force and relative motion through different contact models. DEM treats each particle as a single element with properties such as mass, velocity, position, moment of inertia, etc. In a given time step, its interactions are calculated according to Newton's laws of mechanics. Multiple iterations are performed to update the relevant information of all elements, and finally the motion state of the granular system is obtained [19], [24].

B. Simulation Conditions

In this paper, an equal-scale DEM rotary drum model is established based on the experimental parameters. The rotary drum is made of acrylic material and the particles in the drum are selected as 6 mm green glass beads and 12 mm white glass beads. Large particles are defined as media particles and small particles are defined as crushable ore. The various coefficients of materials mentioned above are obtained from the literature [19], [28]. According to the previous researches, the larger the particle diameter ratio and the lower the particle filling rate in the drums, the easier the axial segregation will occur [19], [24]. Therefore, the diameter ratio of the two particles selected in this article is 1:2, the filling rate is 10% and 20%, and the drum length to diameter (L/D) ratio is 1. And the rotary drum is set to 40 rpm and 80 rpm to represent two working conditions of grinding and crushing, respectively. In addition, the restitution coefficient and friction coefficient have been measured in previous studies through high rebound test and slope test [19], [24]. Table I shows discrete model parameters.

TABLE I
MODEL PARAMETERS USED IN DEM SIMULATION

Parameters	Value
Drum diameter *D* (mm)	400
Drum length L (mm)	400
Drum speed *n* (rpm)	40/80
Drum filling rate F (%)	10/20
Particle volume ratio	1
Particle diameter *d* (mm)	6 / 12
Particle density (kg/m^3)	2, 500
Drum density (kg/m^3)	1, 250
Particle shear modulus *G* (GPa)	22
Drum shear modulus *G* (GPa)	3
Particle Poisson's ratio *v*	0.25
Drum Poisson's ratio *v*	0.35
Restitution coefficient. particle-particle	0.91 / 0.727
Restitution coefficient. wall-particle	0.90 / 0.722
Static friction coeff. particle-particle	0.435
Static friction coeff. wall-particle	0.50
Rolling friction coeff. particle-particle	0.01
Rolling friction coeff. wall-particle	0.055

The main research in this paper is to explore the relationship between particle segregation behavior and the collision energy in the rotating drum, so the contact model used in this paper is Hertz-Mindlin with RVD rolling friction model. The total volume ratio of 6 mm and 12 mm glass balls is 1:1, and initial structure of the filled particles is completely random mixing. All simulation models were realized by a commercial software called EDEM and performed on a workstation with a CPU of AMD Ryzen Threadripper 2950X and 64GB RAM. In all simulation studies, the drum speed is set to 40 rpm and the time step used in models is 25% Rayleigh time step.

C. Experiments

To verify the validity of the DEM model, the particle mixing and segregation process was captured by cameras in different positions. In all experiments and DEM simulations, the rotating drum speed is set to 40 rpm and the sampling time is set to 30 s. Fig. 4 lists the image sequence of radial mixing and segregation obtained by experiment and DEM simulation, corresponding to radial images of the end cover on one drum side (x = 0 mm). In the initial mixing-segregation stage from 0 s to 5 s, the motion trajectories and the overall dynamic repose angle of radial end cover position are very similar in experiment and simulation. As the drum continues to rotate to about t = 10 s, both the overall dynamic repose angles are stable at about 30°. In this case, the radial segregation characteristic is aggravated, with smaller green particles being almost invisible.

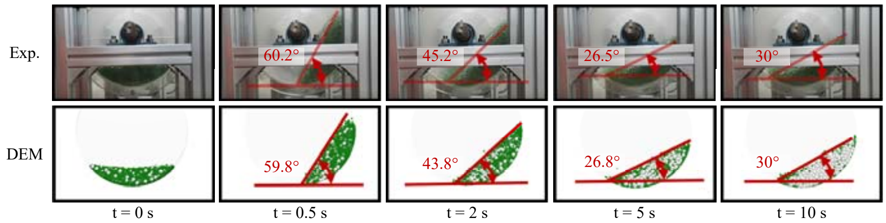


Fig. 4 Radial segregation image sequences (n = 40 rpm, F = 10%).

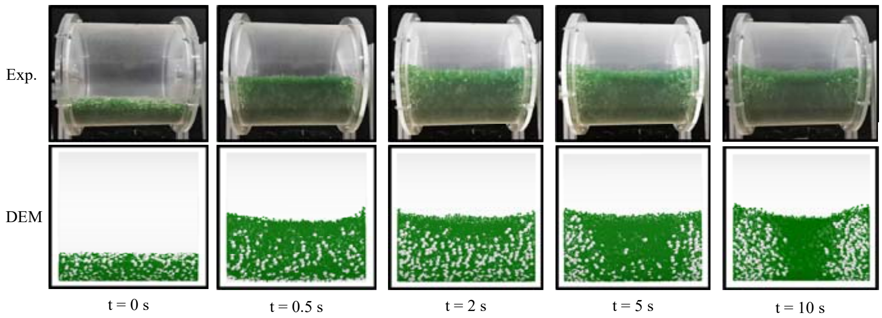


Fig. 5 Axial segregation image sequences (n = 40 rpm, F = 10%)

Then, Fig. 5 shows the axial image sequence acquired by another camera at the axial position of drum (y = 400 mm). With the progress of the mixing process, the binary particles in the rotary drum gradually produced a relatively obvious axial segregation phenomenon. Obviously, radial segregation can coexist with axial segregation, but often occurs earlier than axial segregation, which is consistent with the studies of Chen, Ottino and other collaborators [29], [30]. In addition, combined with DEM simulation and experimental results in Figs. 4 and 5, the deviation of the both dynamic repose angle at different times is less than 5% in radial view. Simultaneously, in the axial view, the appearance and stabilization time of axial segregation in DEM are basically consistent with the experimental results. Therefore, the accuracy of the discrete element model is high and can be used in subsequent research.

IV. Results and Discussions

In this part, firstly, the overall segregation degree of the different diameter particles is quantitatively evaluated during the motion of the drum. Then, the relationship between radial segregation characteristics at different positions of the drum and the corresponding radial RRTE is discussed. Finally, on this basis, this paper studies the relationship between the axial segregation characteristics and the overall crushing efficiency of the rotary drum.

A. Overall Segregation Characteristics of Different Diameter Particles in a Rotary Drum

Based on completing the above model parameter settings, the particle movement in drum is simulated for a total of 30 seconds. As described in the third part, DEM simulation can provide particle position information at each time step. According to the previously proposed ACNN method [19], [24], the overall segregation degree can be evaluated, and the results of the segregation degree of binary particles in the rotating drum at different times can be obtained, as shown in Fig. 6.

Fig. 6 (a) shows the overall segregation characteristics of the two diameter particles in the drum (F = 10%, n = 40 – 80 rpm). On the whole, the overall segregation index of two diameter particles increases with the rotation of the rotary drum, and tends to be stable gradually. In addition, in the long drum with F = 10%, the time for the both diameter particles to reach the steady overall segregation state decreases with the increase of rotation speed, and concomitant steady-state SI also decreases. To express the axial segregation characteristics more clearly, the overall segregation characteristics (t = 10 s) under two working conditions are given as Figs. 6 (a) (ii) and (b) (ii), including radial segregation view and axial segregation view. The large white particles represent 12 mm media and the small green particles represent 6 mm abrasive. In the case of t = 10 s, no matter grinding or crushing, both working conditions form an axial center segregation band-like characteristics dominated by white media particles on both sides and green abrasive particles in the middle.

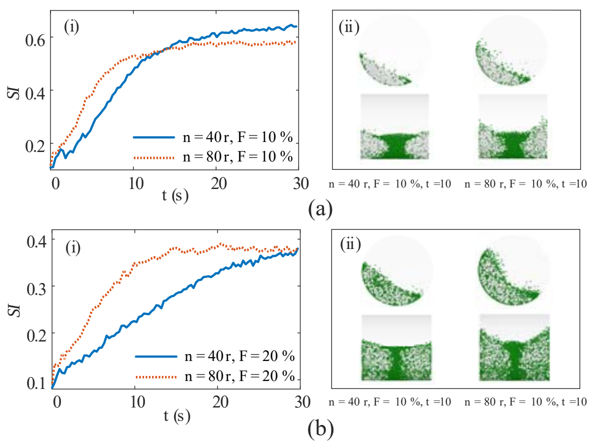


Fig. 6 The overall segregation degree *SI* under different conditions: (a) F = 10%, n = 40 – 80 rpm, (b) F = 20%, n = 40 – 80 rpm

Similarly, Fig. 6 (b) shows overall segregation distribution in a drum with F = 20%. In general, the overall segregation trend of both diameter particles is similar to that of F = 10%. However, compared with F = 10%, the segregation index of these two sets with F = 20% of the rotating drum is lower, and the time to enter the steady state segregation state is significantly delayed. This means that under the condition of the same drum L/D ratio, the particle filling rate has a certain inhibitory effect on the overall segregation characteristics. The higher the particle filling rate, the lower the degree of axial segregation.

B. Quantitative Analysis Based on the RRTE of Radial Surface

Since the collision of white media and green abrasive is directly related to the crushing effect of the rotating drum, the collision loss energy related to grinding and crushing is taken as research object to calculate RRTE. In this paper, the inner diameter D of the drum is 400 mm, and the length L is 400 mm. According to the method in the second section, the whole area of the long drum is divided into a 20×20×20 three-dimensional grid.

Fig. 7 qualitatively compares particle characteristic patterns of surface segregation and internal segregation of the radial section along the axial position of the drum. On the whole, for a long drum with L = 400 mm, although the radial segregation patterns of the symmetrical areas on both sides of the drum are basically the same, the segregation characteristics of the radial surfaces at different positions are still significantly different. For example, segregation patterns dominated by large particles are formed in the radial surfaces near the end covers on both sides, while segregation patterns dominated by small particles are formed in the radial surfaces near the middle of the drum, which are the result of the end-cover effect. Therefore, for a long drum with multiple media particles, the radial surface of a single axial segment cannot be regarded as a quantitative indicator of overall degree of segregation, which is consistent with our previous research [19].

In addition, Fig. 7 shows radial RRTE for different operating conditions (t = 10 s). Due to the uneven distribution of media and abrasive particles along the axial direction of the drum, the crushing effect of each area is inconsistent. Although the radial RRTE can reflect the working effect of each region to a certain extent, it still has limitations relative to the overall (axial) crushing effect. Therefore, radial RRTE may be more suitable for short drums than for longer drums with axial segregation characteristics.

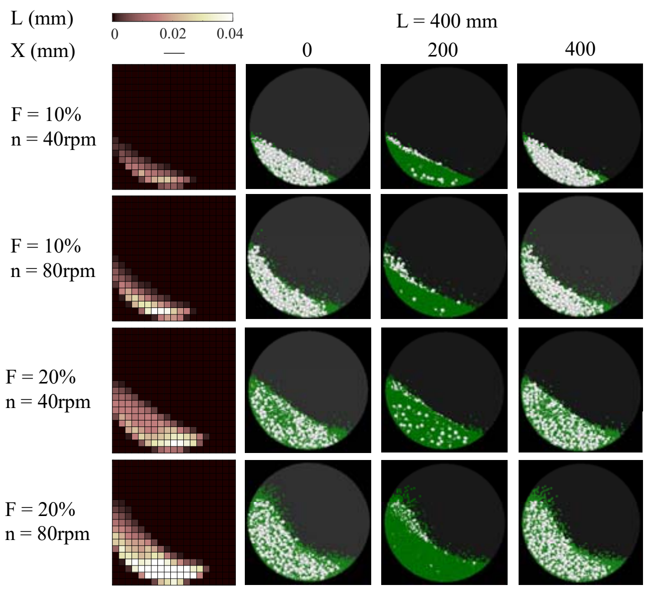


Fig. 7 Radial segregation pattern on the surface and inside of drum and its RRTE (t = 10 s)

C. Quantitative Analysis Based on the RRTE of Axial Surface

Obviously, the axial segregation phenomenon usually exists in the long drum, and the particle distribution along the axial direction varies greatly. The relationship between the RRTE of the axial surface and the overall crushing efficiency needs to be further investigated. This section further studies the RRTE distribution of the long drum axial surface, and explores the relationship between the axial segregation characteristics and the overall grinding efficiency.

Firstly, based on the definition of the proposed RRTE index, we calculate the axial RRTE distribution of the two-diameter media and abrasive particles, which is represented by a color map, as shown in Fig. 8. The calculated RRTE between media and abrasive particles is mainly concentrated on both sides of the drum, which is almost consistent with the axial segregation characteristics of the large white media particle band. In general, the axial segregation characteristics of medium particle band are directly related to the total energy distribution in each region. Therefore, the RRTE of the axial surface can better reflect overall crushing effect than that of radial surface in long drums. Furthermore, a correlation image of the total RRTE value and the overall segregation index *SI* was plotted, as shown in Fig. 9. It is clear that the overall segregation characteristics of the rotating drum directly affect the overall grinding and crushing efficiency. Except for the initial particle lift stage, the total RRTE value decreases with the increase in overall segregation (characteristics) degree. In general, the overall segregation characteristics, especially the axial segregation characteristics, directly affect the RRTE distribution of the medium-particles, which determines the overall grinding and crushing efficiency. The more obvious the axial segregation characteristics in long drums, the more the RRTE of the media-abrasive particles tends to the axial segregation distribution. The inconsistent crushing effect of each area in the long rotary drum results in energy loss, which makes the overall grinding and crushing efficiency lower. Therefore, the influence of the axial segregation characteristics of the medium on the overall crushing effect should be fully considered. In the process of crushing, we try to avoid the axial segregation behavior of equipment such as rotary drums.

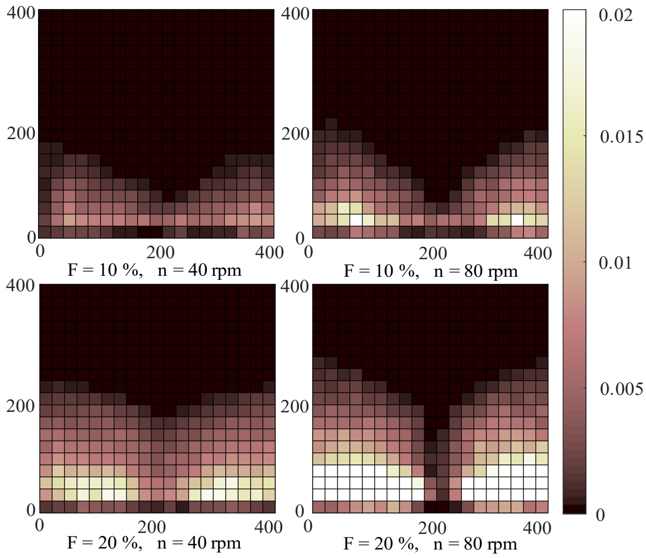


Fig. 8 Axial segregation pattern and its RRTE (t = 10 s)

V. Conclusion

Aiming at the axial segregation phenomenon in the long drum, this paper proposes a RRTE index to evaluate the overall grinding effect of the rotary drum, which is further used to investigate the collision loss energy in the particle grinding process. According to the research results, the conclusions are as follows:

1) The proposed RRTE index quantifies the crushing effect by evaluating relative crushing energy in different areas.
2) The media in long drums is unevenly distributed along axial direction, which makes the RRTE of each radial surface inconsistent, difficultly reflecting overall crushing effect through a single radial surface
3) In long drums, the RRTE of axial surface can better reflect the overall grinding effect than that of the radial surface.
4) The more serious the axial segregation, the worse the overall crushing effect of media-abrasive particles.

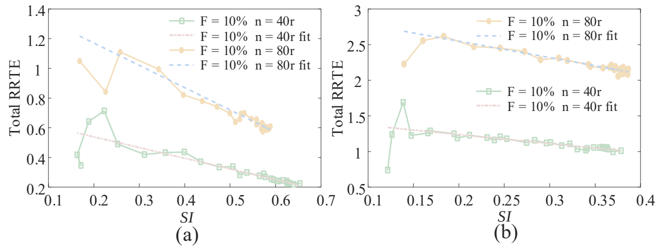


Fig. 9 The relationship between overall segregation degree and RRTE

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