Discrete Element Simulation of Vibration Density Screen

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Abstract. For the aim of sorting non-metallic shredder residue of body of end of life vehicle after disassembly, an innovative density screen is proposed. In this paper, the model of throwing and sliding of plastic and glass scrap of material for this equipment was defined. And then, the numerical simulation of vibration sorting process was carried out by the software of EDEM. The result of simulation showed that, plastic particle and glass particle can be separated at certain frequency and amplitude by this method.

Introduction

Currently, in the disassembly and recycling process of end-of-life vehicles, the vehicle body is generally subjected to packaging, crushing and separation process after disassembly operations^[1]. Magnetic separation and eddy current technologies are adopted in the separation process to separate non-ferrous metal materials, such as steel, aluminum and copper. However, non-metallic materials, such as rubber, plastics, are treated as wastes. Conversely, using mechanical vibration technology to separate these non-metallic materials is a kind of method with low secondary pollution and high separation efficiency. However, the technical parameters of vibration separation equipment have major impact on separation screens is essential. We use discrete element simulation software EDEM to perform numerical simulation and analysis for separation screens under different frequencies, vibration amplitudes and vibration direction angles. Then, the process parameters of density separation screens are obtained.

Model of material on the screen surface

After materials enter the separation device, they perform sliding and throwing movements on the screen surface, thus making them move forward or backward on the screen plate. The movement model is shown in Fig. 1, where F is the vibration direction of screen plate; X direction is the tangential direction of screen plate; Y direction is the normal direction; and G is the gravity of materials^[4].



Note: *F* -Exciting force; *b* -Vibration direction angle; *a* -Screen surface inclination; *G* -Gravity Fig.1 Vibration Density Screen device diagram

The working surface of the vibration density screen conducts simple harmonic movement along the vibration direction. According to kinetic analysis, the displacement equation of the working surface of the density screen is

$$S = A \cdot Sinwt \tag{1}$$

$$v = wA \cdot C \operatorname{os}(wt) \tag{2}$$

$$a = -w^2 A \cdot Sin(wt) \tag{3}$$

$$K = \frac{w^2 A}{g} \tag{4}$$

$$D = \frac{w^2 A}{g} \cdot \frac{Sinb}{Cosa}$$
(5)

where

 κ denote the vibration amplitude;

D denote the throwing index; when it is larger than 1, materials can be thrown up;

- A denote the vibration amplitude of the separation screen;
- *w* denote the angular velocity of the vibration motor;
- *a* denote the inclination of the screen surface;
- *b* denote the vibration direction angle, $(^{\circ})$;

g denote the acceleration of gravity, $(g = 9.81m/s^2)$.

A three-dimensional model of the vibration density separation screen is demonstrated in Fig. 2. The inclination angles of the three screen plates are all 9°. The lengths of the upper, middle, and lower screen plates are 300mm, 250mm, and 250mm, respectively. To increase the computation speed, the widths of the three screen plates are set to 200mm, with the intervals set to 70mm.

The sorting process is realized through the contact and collision between particles and screen plates, so that some particles move upward or downward and different particles are separated. To correctly describe the inter-particle collision and the collision between particles and screen plates, the particle discrete element method is used: elastic - damping - friction - sliding contact mechanical model ^[2,5], as shown in Fig. 3.



Fig.2 3D Model of Vibration Density Screen



Note: K_n -Normal stiffness; K_i -Tangential stiffness; C_n - Normal damping; C_i - Tangential damping; \mathbf{M} - Friction coefficient; F_n -Normal force; F_i -Tangential force; 1. Particle stiffness (spring); 2. Damper; 3. Slider; 4. Friction device Fig.3 Contact mechanics model

According to the calculation of the contact force, the following is obtained:

$$F_{nij} = \left(-k_n a^{\frac{3}{2}} - h_{ni}Gn\right)n$$

$$F_{iij} = -k_i d - h_{ij}G_{ci}$$
(6)
(7)

Where

a denote the overlap amount of particles in normal direction;

G denote the relative velocity between particle *i* and particle *j*; $G = v_i - v_j$;

n denote the unit vector from the Spherical center of particle i to the Spherical center of particle j;

 h_{ni} and k_n denote the normal damping coefficient and normal elastic coefficient of particle *i*, respectively;

 h_{ij} and k_i denote tangential damping coefficient and tangential elastic coefficient, respectively;

 G_{cr} denote the slip velocity of the contact point between two balls;

d denote the tangential displacement of the contact point between two balls.

 $k_n k_t$ and G_{a} denote given by the following equations:

$$k_{n} = \frac{4}{3} \left(\frac{1 - v_{i}^{2}}{E_{i}} + \frac{1 - v_{j}^{2}}{E_{j}} \right)^{-1} \left(\frac{a_{i} + a_{j}}{a_{i}a_{j}} \right)^{\frac{-1}{2}}$$

$$(8)$$

$$k_{t} = 8a^{\overline{2}} \left(\frac{1 - v_{i}}{G_{i}} + \frac{1 - v_{j}}{G_{j}} \right) \left(\frac{a_{i} + a_{j}}{a_{i}a_{j}} \right)$$

$$(9)$$

$$G_{ct} = G - (Gn)n + a_i \Omega_i \times n + a_j \Omega_j \times n$$
⁽¹⁰⁾

where

n and E denote the Poisson's ratio and elastic modulus of the particulate material, respectively; a denote the radius of particles;

The subscriptions i and j represent the contacting particles i and j, respectively;

 G_i and G_j denote the shear modulus of particles *i* and *j*, respectively;

 a_i and a_j denote the radius of particles *i* and *j*, respectively;

 Ω_i and Ω_j denote the angle velocities of particles *i* and *j*, respectively.

Simulation with EDEM

To increase the calculation speed of simulation, the glass particles and plastic particles in Non-metallic of ELV (End of life vehicle) residue are considered as the objects to be screened, without considering other impurities. Glass and plastic both have irregular flat-shaped profiles, as shown in Fig. 4. The physical parameters of glass, plastic and screen surface (steel) are shown in Table 1. The coefficients of restitution of all materials are calibrated as: 0.5 between glass and glass; 0.6 between glass and plastic; 0.3 between glass and screen surface; 0.45 between plastic and screen surface. The coefficients of static friction of all materials are calibrated as: 0.154 between glass and glass; 0.2 between glass and plastic; 0.154 between glass and screen surface; 0.5 between plastic and screen surface. The rolling friction coefficients of all materials are calibrated as: 0.1 between glass and glass; 0.01 between glass and plastic; 0.1 between glass and screen surface; 0.01 between plastic and screen surface. The drop heights of glass and plastic are 40mm, with a speed of 0.05m/s. The producing speeds of glass and plastic are both 25 pieces per second. The generation time of particles is 5s, and the simulation time is 13.5s in total.



Fig.4 3D Model of shredded materials

Table.1 Material physics properties				
Particle	Poisson's ratio	Shear modulus /Mpa	Density/ $(kg \cdot m^{-3})$	
Glass	0.25	220	2465	
Plastic	0.3897	862.2	1400	

The calculation equation of the time steps is obtained according to Rayleigh wave method

$$T = \frac{pR}{0.163v + 0.877} \sqrt{\frac{r}{G}}$$
(11)

where

R denote the particle radius (m);

r denote the particle density $(kg \cdot m^{-3})$;

G denote shear modulus (Mpa);

n is the Poisson's ratio.

In the simulation of EDEM, the numbers of glass and plastic particles on the screen surface, the trajectories, and the number of particles falling into the front and back troughs can be displayed in real time. After simulation, statistical analysis is performed for the numbers of glass and plastic particles falling into the front and back troughs^[6].

Motion simulation of particles on screen surface.By referring to relevant documents and manuals, it can be concluded that the vibration amplitude, frequency and vibration direction angle have the most significant impact on screen separation. Therefore, these three parameters are the parameters to be optimized in analyzing the screen separation process.

Effect of vibration amplitude on separation. Under the condition that the frequency is 12 Hz, and the vibration direction angle is , the vibration amplitudes of 4, 5, and 6 mm are selected for simulation. Fig. 5 shows the X components of speed for plastic particles from 0s to the end of simulation (13.5s). The speed variation from the moment when materials drop on the screen surface to 3.17s is the same as that from 3.17s to the moment when all the plastic particles drop on the screen surface (5.55s).



Fig.5 Speed variation in X direction of plastic particles under different amplitudes

During the period from the phase when the plastic particles start to contact the screen surface to the phase when all particles fall into the front trough, the average speeds in X-direction for amplitudes of 4, 5, and 6 mm are 0.0063, -0.0056, and -0.0189 m/s, respectively. After all plastic particles fall, the

particle layer becomes thin and the speed increases with the proceeding of screening. When most plastic particles fall into the front trough, the speed of the rest plastic particles decreases dramatically. When the amplitude is 6mm, all the plastic particles fall into the front trough at 9.42s, with 3 glass particles falling into the front trough. When the amplitude is 5mm, all the glass particles fall into the back trough at 8.81s, with 6 plastic particles still on the screen surface. When the amplitude is 4mm, all the glass particles fall into the back trough at 8.09s, with 20 plastic particles still on the screen surface. It can be concluded that the larger the amplitude, the higher the forward speed, and the shorter the time for separating plastic particles. However, when the amplitude is 6mm, there are 3 glass particles falling into the front trough, causing impurity in plastic particles, while when the amplitude is 4 or 5mm, there is no loss.

	4mm	5mm	6mm
Plastic	92.8%	91.2%	92.8%
Glass	100%	100%	97.6%

Table 2 Separation rate of materials with different amplitudes

It can be concluded from Table 2 that the larger the amplitude is, the lower the separating ratio of glass particles is. The separating ratio of plastic particles for 4mm is the same as that of 6mm. However, the separating ratio of glass particles for 4mm is relatively higher. Therefore, in the cases where the other conditions are the same, the amplitude of 4mm is conducive for separating the two kinds of particles.

Effect of frequency on separation. It can be concluded in the analysis of Section 3.2.1, taking into account both separation efficiency and separation impurities, the performance of amplitude 4mm is relatively satisfactory. Therefore, the amplitude of 4mm is selected when analyzing the effect of frequency on separation performance, with vibration direction angle set to . The simulation is carried out for frequencies of 12, 16.167, and 23.833Hz.



Fig.6 Speed variation in X direction of plastic particles under different frequencies.

It is clear in Fig. 6 that in case where the other conditions are the same, with the increase of frequency, the forward movement speed of particles increases. The X-direction speeds are 0.0063, -0.0268, and 0.0419m/s for frequencies 12, 16.167, and 23.833 Hz, respectively. When the frequency is 23.833Hz, there are 8 plastic particles on the screen surface without falling into the front trough at the end of simulation (at 13.5s). At this moment, the separating ratio of plastic particles is the lowest. However, all the glass particles have fallen into the back trough. When the frequency is 16.167 Hz, all the plastic and glass particles is the lowest, while that of plastic particles is the highest. When the frequency is 12 Hz, all the glass particles have fallen into the back trough by 8.09s, while most plastic particles have fallen into the front trough by 13.25s. The combined separating ratio of the plastic and glass particles is the highest.

Effect of vibration direction angle on separation. It can be concluded from the two previous groups of simulation experiments that under the condition that the amplitude is 4 mm and the frequency is 2Hz, the vibration direction angles of 40° , 45° , 50° , 55° and 60° are selected.



Fig.7 Speed variation in X direction of plastic particles under different vibration direction angles

It is clear in Fig. 7 that, the separating ratio is the lowest when . There are 3 plastic particles and 4 glass particles on screen surface at 13.5s. When the inclination is , the separating ratio is the highest. However, there is one glass particle falling into the front trough, causing loss. In the range of 40° to 60° , with the increase of vibration direction angle, the separating ratio of glass particles decreases. The separating ratio of plastic particles reaches maximum at 50° , while minimum at 60°

Conclusions

In the cases where the other conditions are the same, with the increase of frequency and amplitude, (i.e., the throwing index and vibration strength increase), the particles' forward speed along the screen surface increases, and the separation efficiency improves. However, the increase of frequency and amplitude also causes the increase of impurities. Therefore, the increase of impurity should also be considered when the separation speed is increased.

In the cases where other conditions are the same, the forward speed of plastic particles reaches the maximum at the direction angle of 55°. For other angles, the fluctuation of the forward speed of plastic particles is large and within a certain range. When the vibration direction angle is the smallest, the throwing index is the lowest. The movement of plastic particles on the screen surface is mainly sliding, and the moving speed of the screen surface is just the moving speed of plastic particles. Therefore, when the angle is 40°, the speed fluctuation is the largest. With the increase of vibration direction angle, the throwing index increases, and the separation efficiency decreases. The separation efficiency reaches maximum when the vibration direction angle is 50°, with impurity content almost zero. Thus, it can be concluded by analyzing the simulation result that the best separation performance is obtained when the vibration amplitude is 4mm, the frequency is 12 Hz, and the direction angle is 50°.

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