NUMERICAL SIMULATION AND EXPERIMENT OF VIBRATION PELLETIZER BASED ON EDEM
/
基于 EDEM 振动丸化包衣机的数值模拟与试验

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DOI: https://doi.org/10.35633/inmateh-63-48

Keywords: *Vibration; Pelleting; Coating machine; Mixing uniformity; EDEM*

ABSTRACT
In order to quantitatively describe the influence between the mixing process and the pelleting quality of the vibration pelletizer, this paper uses EDEM to conduct a numerical simulation study on the uniformity of the seeds and powder mixing of the pelleting machine under vibration force field. Meanwhile, a single factor test was established to verify the feasibility of numerical simulation. The results show that the coefficient of variation CV is the smallest and the mixing uniformity between the seeds and powder is the highest when the vibration frequency is 20Hz, the rotation speed is 45r/min, the tilt angle is 40° during numerical simulation. The pelleting qualified rate J and single seed rate P as the test index of the mixing uniformity of seed pelleting shows the optimum value in the single factor test, EDEM can be used to analyse the mixing uniformity and pelleting quality in pelletizer. The results of orthogonal experiment indicated that the best combination of parameters was obtained as follows: vibration frequency of 20Hz, rotation speed of 45r/min and tilt angle of 40°, the mixing uniformity of seeds and powder and the pelleting quality of Agropyron seeds are the highest. This study can effectively provide reference for design of pelleting machine of small seeds under vibration force field.

摘要
为了定量描述振动丸化包衣机混合过程与丸化包衣质量间的影响规律，本文采用EDEM对丸化包衣机在振动力场作用下的种、粉混合均匀度进行数值模拟研究，同时利用单因素试验验证数值模拟的可行性。结果表明：当丸化包衣机的振动频率、包衣锅转速、包衣锅倾角分别设定为 20Hz 、45r/min、40°时，变异系数Cv在数值模拟过程中均出现最小值，表明种、粉颗粒间达到较优的混合均匀度；丸化合格率J和单籽率P作为种子丸化包衣混合程度的试验评价指标在单因素试验中均表现出最佳值，EDEM可以用于丸化包衣机混合均匀程度及丸化质量的数值模拟分析。正交试验结果得到振动丸化包衣机最优工作参数组合：振动频率 20Hz、包衣锅转速为 45r/min、包衣锅倾角为 40°，在此工作参数组合下种子与粉料能达到较为理想的混合均匀度，冰草种子丸化包衣质量较高，研究结果可为振动作用下小粒种子的丸粒化包衣机设计提供参考依据。

INTRODUCTION
Seed pelleting is a novel type of seed processing technology that uses pelleting equipment to uniformly apply powder, seed coating agent and other additives with specific functions to the surface of seeds to form pelleted seeds, which improved the germination rate and survival rate of seeds (*Wang, 2011; Lei, 2010*). The key to the quality of pelleting depends on the pelleting performance of the pelleting equipment, which is also a significant issue for scholars at home and abroad. The research focus of domestic and foreign scholars on the coating machine is mainly concentrated in the development of pelleting equipment suitable for different types of seeds. However, there are few researchers on the content of pelleting qualified rate, optimization of coating mechanism and working parameters of rotary equipment (*Sang, 2015*).

The main function of the pelleting equipment is to promote the mixing uniformity of materials. Its mixing effect is directly related to the pelleting quality, pelleting qualified rate and single seed rate. Therefore, it is of great significance to study the mixing uniformity between seeds and powder in the coater to improve the quality of the pelleting (*Yang, 2015*).

At present, some scholars have studied the movement law of materials in the drum and the mixing effect between the materials (*Su, 2014; Jiang, 2019*). Due to the complexity of the mixing movement of materials, the special characteristics and opacity of the mixing equipment such as pelleting drums and coaters, it is impossible to dynamically track and detect the mixing process of materials by means of experiments (*Koteswara, 2013*). Therefore, the method of computer numerical simulation is used to study the mixing effect and movement law between materials by many researchers. Discrete Element Method (DEM) proposed by Cundall in 1971 is the most widely used. You Ying established a discrete droplet spray analysis model based on DEM to simulate the effects of working parameters on particle motion and tablet coating uniformity (*You, 2019*). Liu Wenjun used discrete element theory to simulate and analyse the mixing characteristics of materials in coal mine rotary (*Liu, 2017*). Dun Guoqian conducted EDEM simulation on the filling characteristics of different varieties of soybean seeds (*Dun, 2019*). Zhang Tao used DEM theory to study the movement law of the corn population in the seed metering chamber (*Zhang, 2016*). Throughout the above studies, it was found that the mixing between materials is a very complicated physical behaviour, and it is impossible to express the quantitative uniformity of the mixing uniformity. In this paper, the coefficient of variation CV is used as the evaluation index of the mixing uniformity. Besides, the EDEM is used to conduct a numerical simulation study for the mixing uniformity of Agropyron seeds and powder in the vibrating coater. In addition, the mixing effect and law between seeds and powder under different working conditions were compared by simulation and verification experiments, in order to obtain the best combination of parameters of pelleting machine.

MATERIALS AND METHODS

Pelleting machine structure and principle

The pelletizer for Agropyron seed overall structure is shown in Fig.1. It contained seed supply system, powder supply system, liquid supply system, pelleting device, vibration system, and control system. When the pelleting machine is working, seeds and powder are lifted up to the respective hoppers. The seed agent is mixed according to a certain proportion, and is atomized into the coater by high-pressure pump. The coater starts to rotate under the drive of a rotating motor, which drives the Agropyron seeds and powder in the coater to rotate, and there are other complex movements under the action of friction. In this time, the powder is adhered to the surface of the seed due to seed coating agent. Furthermore, powder and seed coating agent continue to be added until the desired seed size is reached, and the whole pelleting process is ended. The driving motor, tilt angle adjustment mechanism and vibration exciter are used to adjust the rotation speed, tilt angle and vibration frequency of the coater respectively.

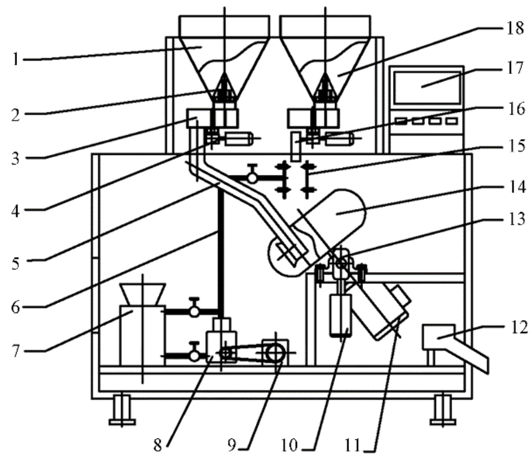


Fig. 1 – Structure figure of the pellet coating machine

1. Powder feed inlet 2. Feed inlet valve 3. Weighing system 4. Step motor 5. Powder conveying pipeline 6. Liquid medicine pipe 7. Liquid medicine storage tank 8. High pressure pump 9. Motor 10. Rotary stepper motor 11. Coater motor 12. Outlet port 13. Electric vibration exciter 14. Coater 15. Nozzles 16. Seed diffuser 17. Controller 18. Seed feed inlet

Basic principles of Discrete Element Method

The force of pelleted seed includes the force between seed and seeds or between seeds and coater. If the coater is equivalent to seeds of infinite diameter, the force between seeds and coater can be uniformly regarded as the force between the seeds and the analysis of force is shown in Fig.2.

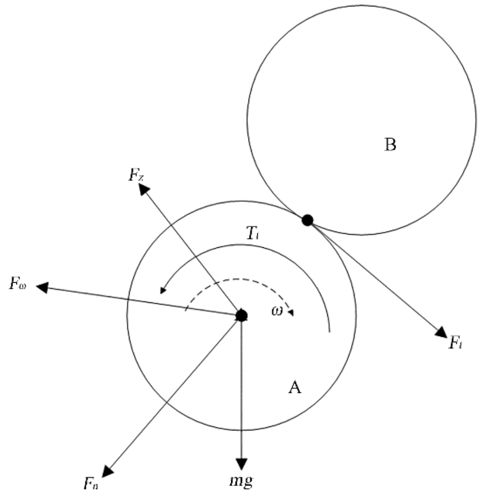


Fig. 2 – Force analysis diagram between the seeds and between the seeds and the coater

It can be seen from Fig.2 that the combined external force ΣF and the combined external moment ΣM of seed i can be expressed by the following equation:

$$\begin{aligned} m_i u_i &= \sum F \\ I_i \alpha_i &= \sum M \end{aligned} \tag{1}$$

where:

u_i - the acceleration of seed particle i, [m/s^2];
α_i - the angular acceleration of seed particle i, [rad/s];
m_i - the mass of seed particle i, [g];
I_i - the rotational inertia of seed particle i, [kg·m²].

$$\begin{cases} \sum F = F_g + F_r + F_z + \sum_{j=1}^{n_i} \left(F_{n,ij} + F_{t,ij} \right) \\ \sum M = \sum_{j=1}^{n_i} \left(M_{t,ij} + M_{r,ij} \right) \end{cases} \tag{2}$$

In equations (2): F_g - gravity, [N]; F_r - centrifugal force, [N]; F_z-excitation force, [N]; $F_{n,ij}$ - the normal contact force of particle i subjected to particle j, [N]; $F_{t,ij}$ - the tangential contact force of particle i subjected to particle j, [N]; $M_{t,ij}$ - the tangential contact torque of particle i subjected to particle j, [N·m]; $M_{r,ij}$ - the friction torque of particle i subjected to particle j, [N·m]; n_i - the total number of particles in contact with particle i.

Discrete element simulation

Simulation parameter settings

This paper aims at the research of natural Agropyron seeds suitable for growing in arid and semi-arid areas. The intrinsic physical parameters and contact parameters of Agropyron seeds were measured by means of stacking and kinematic experiments. The measurement results are shown in Table 1. The seed particles are modelled and analysed using discrete element simulation software EDEM for three-dimensional solid modelling, and the Agropyron seeds are created by the overlapping of multiple spheres (ellipsoid with a long semi-axis a=2.5mm, short semi-axis b=1.2mm, and a thickness of 2.4mm). The three-dimensional solid model is shown in Fig.3.

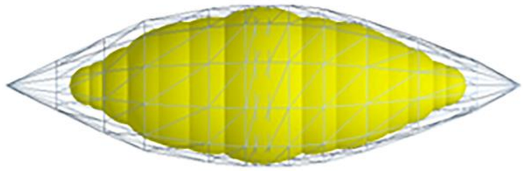


Fig. 3 – Simulation model of Agropyron seeds

EDEM simulation parameters of Agropyron seeds **Table 1**

Test object	Simulation parameters	Value
Agropyron seed	Density / [kg·m^{-3}]	763
	Shear modulus / [Pa]	1.08×10^{7}
	Poisson's ratio	0.28
Coater	Density / [kg·m^{-3}]	7890
	Shear modulus / [Pa]	7.0×10^{10}
	Poisson's ratio	0.28
Powder	Density / [kg·m^{-3}]	978
	Shear modulus / [Pa]	1.1×10^{7}
	Poisson's ratio	0.25
Seeds and seeds	Coefficient of static friction	0.5
	Coefficient of collision recovery	0.3
Seeds and coater	Coefficient of static friction	0.4
	Coefficient of collision recovery	0.4
Seeds and powder	Coefficient of static friction	0.25
	Coefficient of collision recovery	0.25
Powder and coater	Coefficient of static friction	0.3
	Coefficient of collision recovery	0.3
Powder and powder	Coefficient of static friction	0.25
	Coefficient of collision recovery	0.25

Simulation model of coater

The geometric model of the coater of the Agropyron seed was established using CATIA 3D modelling software in Fig.4. The main parameters of the coater are shown in Table 2.

Basic parameters of pelleting coater **Table 2**

Item	Units	Parameters
Maximum diameter of coater	mm	400
Calibre of coater	mm	200
Vibration acceleration of coater	m/s^2	9.81

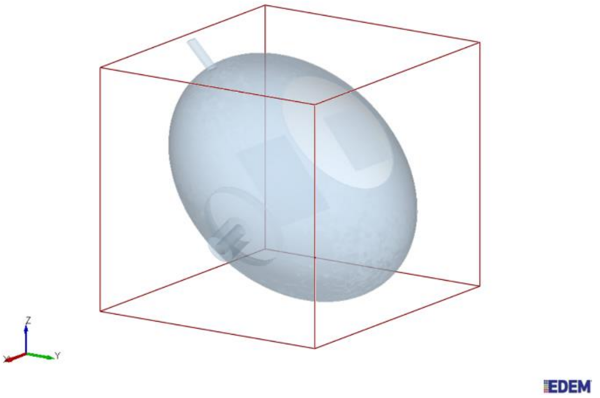


Fig. 4 – The geometric model of Agropyron seed coater

Simulation and experiment of mixing process between seeds and powder

Evaluation parameters of mixing uniformity

In order to be able to quantitatively analyse the mixing uniformity between seeds and powder, the coefficient of variation is used as an evaluation parameter to measure the mixing degree between seeds and powder.

Through the Grid Bin Group module in the selection function in the EDEM post-processing, the entire mixed simulation of seeds and powder is divided into square grids of equal size, as shown in Fig.5. The entire simulation time is set to 15s, the number of seeds and powder particles in each grid is output at a time interval of 3s, and the coefficient of variation of powder particles is calculated.

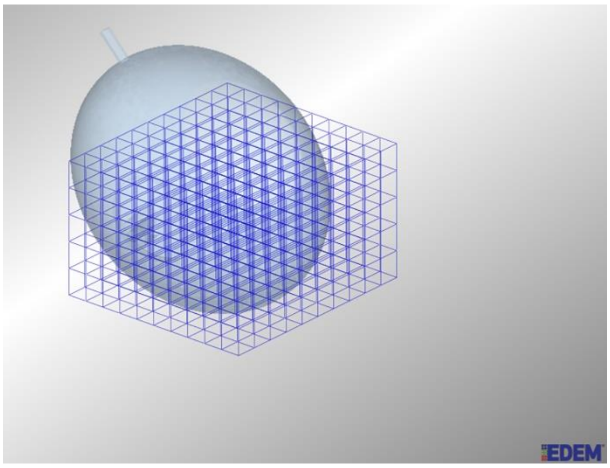


Fig. 5 – Schematic diagram of meshing of EDEM simulation model

Assuming that the total number of divided grids is m, the number of powder particles in the k^{th} grid is b_k, and the total number of seeds and powder particles in the grid is d_k, then the percentage of powder particles in each grid is:

$$g_k = \frac{b_k}{d_k} \tag{3}$$

The theoretical optimal mixing degree ε is:

$$\varepsilon = \frac{\sum_1^m b_k}{\sum_1^m d_k} \tag{4}$$

The dispersion X_k of the powder particles in the k-th grid is:

$$X_k = \frac{g_k}{\varepsilon} \tag{5}$$

Then the standard deviation S_x is:

$$S_x = \sqrt{\frac{\sum_1^m (X_k - \bar{x})}{m-1}} \tag{6}$$

In equations (6): $\bar{x} = \sum_1^m \frac{X_k}{m}$

Then the coefficient of variation Cv of the powder particles is:

$$C_v = \frac{S_x}{\bar{x}} \tag{7}$$

The coefficient of variation can objectively reflect the degree of mixing uniformity between particles. The smaller the coefficient of variation, the better the mixing uniformity. It has been used to evaluate the axial mixing degree of particles in a rotating device.

In order to verify the reliability of the simulation analysis, the pelleting qualified rate J and the single seed rate P were used as the test evaluation index of the mixing degree of seeds and powder. The coating agent was completely coated on the surface of the seed as pelleting qualified. Only one particle of Agropyron seeds in the pelleted seeds accounted for a percentage of the total number of pelleted seeds tested is called single seed rate.

$$J = \frac{Z_h}{Z_b + Z_h} \times 100\% \tag{8}$$

$$P = \frac{D_d}{D_d + D_f} \times 100\% \tag{9}$$

where:

J - pelleting qualified rate, [%];

Z_h - the number of particles completely coated with Agropyron seeds, [-];

Z_b - the number of particles incompletely coated with Agropyron seeds, [-];

P - single seed rate, [%];

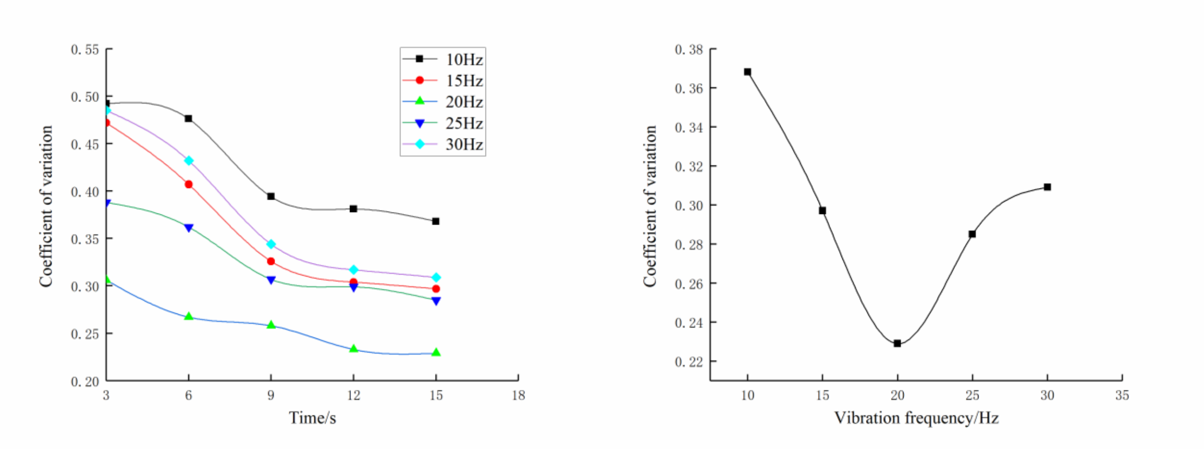
D_d - the number of single seed of Agropyron seeds in the total of pelleted seeds, [-];

D_f - the number of multi-seeds of Agropyron seeds in the total of pelleted seeds, [-].

Simulation and test analysis

Effect of vibration frequency on mixing uniformity

In order to study the effect of vibration on the mixing uniformity, the discrete element software EDEM was used to set the rotation speed of the coater, the tilt angle of the coater, and the amplitude of vibration to 45 r/min, 45°, and 2 mm, respectively, and the vibration frequency was set to 10 Hz, 15Hz, 20Hz, 25Hz, 30Hz to simulate and analyse the effect of vibration frequency on the uniformity of seeds and powder mixing. The simulation results are shown in Fig.6, and the test verification results are shown in Fig. 7.



(a) Variation coefficient of powder particles under different vibration frequencies

(b) Variation coefficient of powder particles at different vibration frequencies at 15s

Fig. 6 – Effect of vibration frequency on mixing uniformity

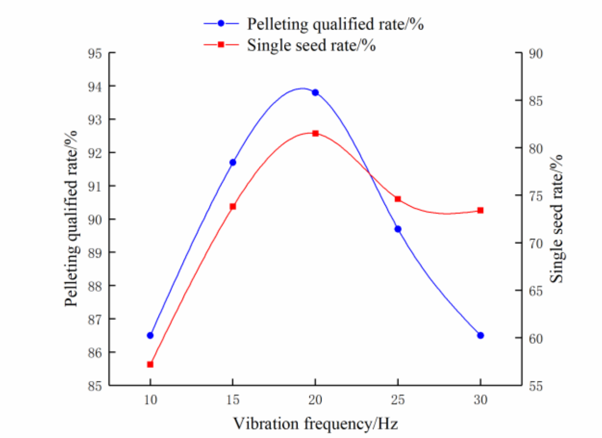
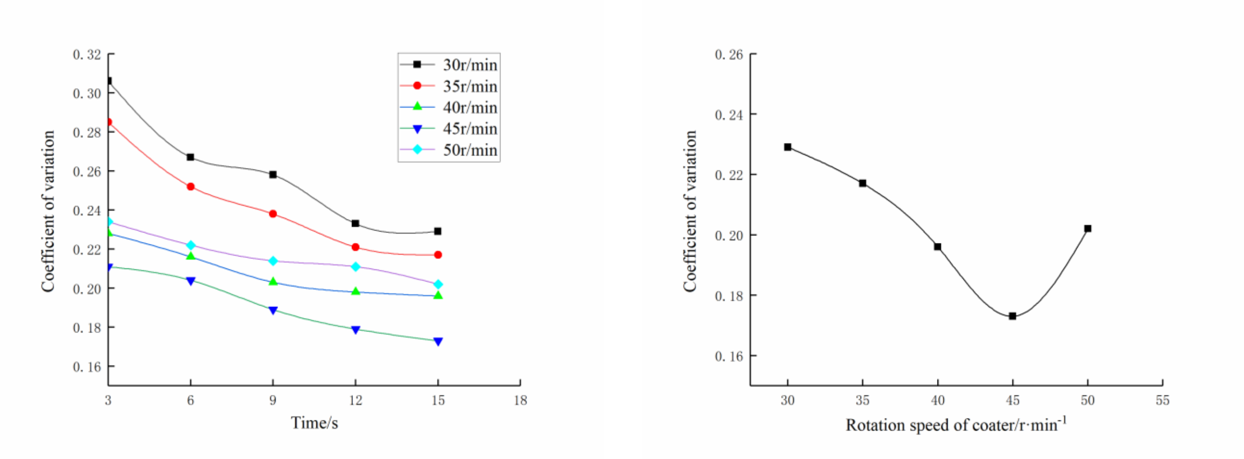


Fig. 7 – Experimental verification of the effect of vibration frequency on mixing uniformity

It can be seen from Fig.6 (a) that when the vibration frequency is 10 Hz, 15 Hz, 20 Hz, 25 Hz, and 30 Hz, the variation trend of the coefficient of variation during the mixing process decreases with the increase of time, and tends to be stable at 12 s. When the time is from 3s to 9s, the variation coefficients of the vibration frequency of 15Hz and 30Hz vary greatly, which is not conducive to the uniform mixing of seeds and powder. When the vibration frequency is 10Hz, 20Hz, 25Hz, the whole mixing process is relatively stable, and the variation range of the coefficient of variation is small. In general, when the vibration frequency is 20Hz, the time required is shorter, the coefficient of variation is smaller, and the mixing uniformity is better than other vibration frequencies. As can be seen from Fig.6 (b), the vibration frequencies are 10Hz, 15Hz, 20Hz, 25Hz, and 30Hz, respectively, the coefficient of variation tends to decrease first and then increase. When it is 20Hz, the coefficient of variation reaches the minimum value of 0.229, and the seeds and powder can reach a uniform state faster and have a better mixing uniformity. It can be seen from the test results in Fig. 7 that both the pelleting qualified rate and the single seed rate have a tendency to increase first and then decrease. At 20 Hz of vibration frequency, both the pelleting qualified rate and single seed rate reach the maximum, indicating that when the vibration frequency is at 20Hz, the mixing uniformity of seeds and powder is the best, and the quality of the pelleting is high.

Effect of coater rotation speed on mixing uniformity

The discrete element software EDEM was used to set the tilt angle of the coater to 45°, the vibration frequency to 20 Hz, and the amplitude to 2 mm. The rotation speed of the coater was set to 30 r/min, 35 r/min, 40 r/min, 45 r/min, 50 r/min to simulate and analyse the effect of the coater speed on the mixing uniformity of seeds and powder. The simulation results are shown in Fig. 8, and the test verification results are shown in Fig. 9.



(a) Variation coefficient of powder particles at different rotation speeds of coater   *(b) Variation coefficient of powder particles at different rotation speeds of coater at 15s*

Fig. 8 – Effect of coater rotation speed on mixing uniformity

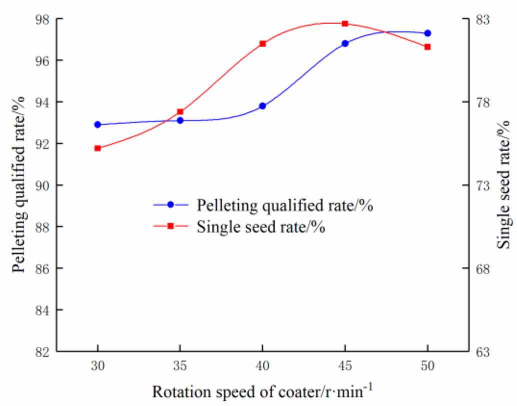


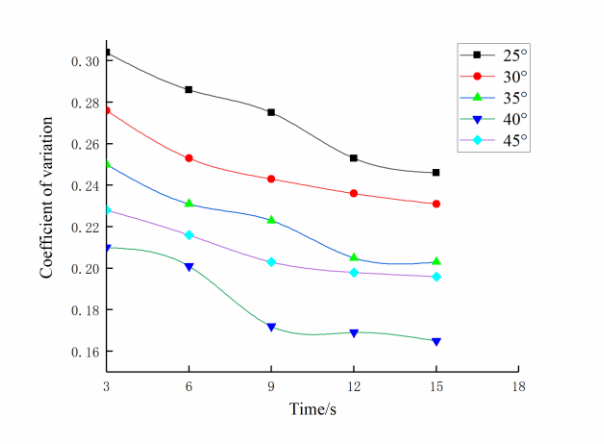
Fig. 9 – Experimental verification of the effect of coater rotation speed on mixing uniformity

It can be seen from Fig. 8 (a) that when the rotation speed is 30r/min, 35r/min, 40r/min, 45r/min, 50r/min, the variation trend of the coefficient of variation in the mixing process decreases with the increase of time. When the rotation speed is 30r/min, 35r/min, the coefficient of variation at 3s is much greater than 40r/min, 45r/min, 50r/min, and gradually stabilizes at 12s, the variation range of the coefficient of variation in the whole mixing process is large and has poor mixing stability. When the rotation speed is 40r/min, 45r/min, 50r/min, the whole mixing process is relatively stable and the variation coefficient variation range is small. Overall, when the speed is 45r/min, the time required is shorter and the mixing degree is better than other speeds, the coefficient of variation is smaller.

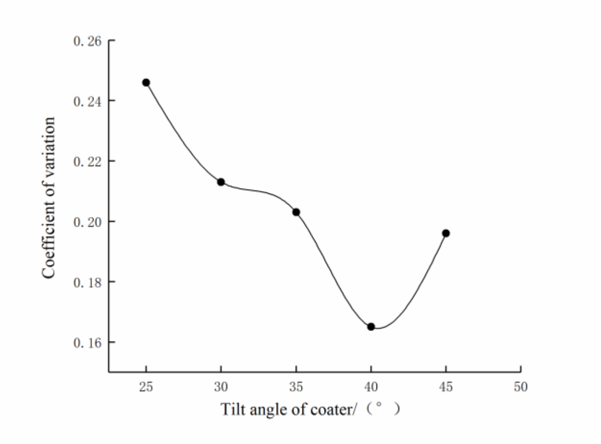
As can be seen from Fig. 8(b), when the rotation speed of the coater is 30r/min, 35r/min, 40r/min, 45r/min, 50r/min, the coefficient of variation is 0.229, 0.217, 0.196, 0.173, 0.202, which shows that when the speed of the coater is 45r/min, the coefficient of variation is small. It can be concluded that the seeds and powder can reach a uniform state faster and have a better mixing uniformity. It can be seen from the test results in Fig. 9 that when the speed of the coater is 45r/min, the pelleting qualified rate and the single seed rate reach the maximum, indicating that the mixing uniformity of seeds and powder is the best and the quality of pelleting seeds is higher.

Effect of the coater tilt angle on mixing uniformity

The discrete element software EDEM was used to set the rotation speed, vibration frequency and amplitude of the coater to 45r/min, 20Hz and 2mm respectively. The tilt angle of the coater was set to 25°, 30°, 35°, 40° and 45° to simulate and analyse the effect of the coater tilt angle on the mixing uniformity of seeds and powder. The simulation results are shown in Fig. 10, and the test verification results are shown in Fig. 11.



(a) Variation coefficient of powder particles under different tilt angle of coater



(b) Variation coefficient of powder particles under different tilt angle of coater at 15s

Fig. 10 - Effect of coater tilt angle on mixing uniformity

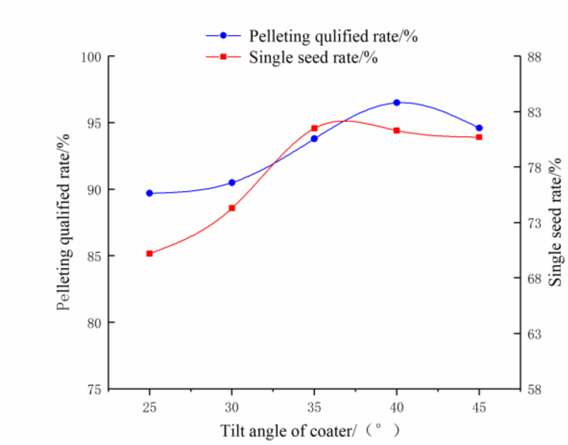


Fig. 11 – Experimental verification of the effect of the coater tilt angle on the mixing uniformity

It can be seen from Fig. 10 (a) that when the coater tilt angle is 25°, 30°, 35°, 40°, and 45°, the variation trend of the coefficient of variation during the mixing process decreases with time. When the tilt angle of the coater is 25°, 30°, 35°, 45°, the variation coefficient and the change range of the whole mixing process is stable and gradually stabilizes in 12s. When the tilt angle of the coater is 40°, the coefficient of variation has a small amplitude change during the period of 6s to 9s. In general, when the tilt angle of the coater is 40°, the time required is shorter and the coefficient of variation is smaller, it can be concluded that the mixing degree is better than other tilt angles. As can be seen from Fig. 10 (b), when the tilt angles of the coater are 25°, 30°, 35°, 40°, and 45° , the coefficient of variation are 0.246, 0.231, 0.203 , 0.165, 0.196. It shows that when the tilt angle of the coater is 40°, the coefficient of variation is small, the seeds and powder not only can reach a uniform state faster but also have a better mixing degree. It can be seen from the test results in Fig. 11 that during the entire test, the pelleting qualified rate has a tendency to increase first and then gradually stabilizes with the increase of the tilt angle, the single seed rate increases first and then increases with the increase of the tilt angle. The results shows that when the pelleting qualified rate and the single seed rate reached the maximum, the tilt angle of the coater is 40°, which verifies the authenticity and feasibility of the simulation results.

Orthogonal test

In order to determine the optimal working parameters combination of Agropyron seeds pelleting machine, the orthogonal test of 3 factors and 3 levels was conducted with pelleting qualified rate and single seed rate as evaluation indexes. L_9 (3^2) orthogonal table was selected, and the test results are shown in Table 3. The experiment was carried out on a self-designed vibrating pelleting machine. The ratio of seed to powder was 1:50, and the ratio of seed to binder was 3.5:1.

Table 3

Orthogonal test plan and results

Test number	Coater rotation speed [r/min]	Coater vibration frequency [Hz]	Coater tilt angle [°]	Pelleting qualified rate [%]	Single seed rate [%]
1	40	10	35	93	75
2	40	15	40	95	76
3	40	20	45	91	73
4	45	10	45	95	78
5	45	15	35	94	74
6	45	20	40	98	82
7	50	10	40	96	78
8	50	15	45	93	73
9	50	20	35	97	81

Range analysis and determination of optimal working parameters combination

According to the results of orthogonal test, the range analysis of pelleting qualified rate and single seed rate was conducted. The results are shown in Table 4.

Table 4

Range analysis of the pelleting qualified rate and single seed rate

	Parameters	Coater rotation speed A [r/min]	Coater vibration frequency B [Hz]	Coater tilt angle C [°]
Pelleting qualified rate	X_{1n}	279	284	284
	X_{2n}	287	282	289
	X_{3n}	286	286	279
	R_n	2.7	1.3	3.3
Single seed rate	X_{1n}	224	231	230
	X_{2n}	234	223	236
	X_{3n}	232	236	224
	R_n	3.3	4.3	4.0

Note: X_{1n} is the sum of test indexes of level i corresponding to the factors in column n (i = 1,2,3)

The calculation formula of range is as follows: $R_n = \max(\bar{X}_{1n}, \bar{X}_{2n}, \bar{X}_{3n}) - \min(\bar{X}_{1n}, \bar{X}_{2n}, \bar{X}_{3n})$.

It can be seen from table 4 that the range values under each factor are not equal, which indicates that the influence of the change of corresponding level of each factor on the test results is not the same. According to the range values in Table 4, the order of importance of three factors (rotation speed of coater, vibration frequency of coater and tilt angle of coater) on pelleting qualified rate is C > A > B. The order of importance to single seed rate was B > C >A.

Considering the two evaluation indexes, the optimal combination of working parameters is A2B3C2. The results showed that the optimal working parameters of the pelleting machine of Agropyron seeds were as follows: the rotation speed of the coater was 45r/min, the vibration frequency of the coater was 20Hz, and the tilt angle of the coater was 40 °. Under this working parameter combination, the mixing uniformity of the seed and the powder material, the qualified rate of pelleting and the single seed rate were higher.

CONCLUSIONS

1) The discrete element simulation model of Agropyron seeds pelleting machine was established by using EDED simulation software. The variation coefficient CV was used as the evaluation index to determine the influence of the vibration frequency, rotation speed and tilt angle on mixing uniformity. According to the simulation results, when the vibration frequency of coater is 20Hz, the rotation speed of coater is 45r/min, and the tilt angle of coater is 40 °, the best mixing state and high mixing uniformity can be achieved.

2) When the coefficient of variation is at the minimum value, the corresponding test indexes of pelleting qualified rate and single seed rate reach the highest value, with high pelleting quality and the best mixing uniformity. The feasibility of single factor numerical simulation is verified.

3) Taking the pelleting qualified rate and single seed rate as evaluation indexes, the orthogonal test of 3 factors and 3 levels was conducted. The results showed that the optimal working parameters of the pelleting machine for Agropyron seeds was A2B3C2.

ACKNOWLEDGEMENTS

We acknowledge that this work was financially supported by National Natural Science Foundation Project "Research on soil wind erosion monitoring system based on wireless sensor network and its key technologies (41361058)" and "Research on seed pelleting parameters and coating mechanism under the vibration force field (2018MS05023)".

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