NUMERICAL SIMULATION AND EXPERIMENTAL STUDY OF INNER FLOW FIELD OF SEED PELLETING PREMIXER IN SPOUTED FLUIDIZED BED
/
喷动式流化床种粉丸化预混合装置内流场数值模拟与试验

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ABSTRACT
In order to explore the temporal and spatial distribution and motion state of the grains of wheatgrass (Agropyron) seeds and powder in pelleting process, and to find the optimal inlet air speed of pelleting premixer, the pelleting forming mechanism was revealed. Based on Herz-Mindlin contact theory, the contact mechanics model of seed and powder was established. Besides, CPFD software was used to model and simulate the pelleting premixer, and the contact, collision and friction rules among particles were analysed. The simulation and experimental results show that with the increase of inlet wind speed, the bed expansion increases and the unit volume particle concentration decreases, while the air pressure difference only slightly increases. When the inlet wind speed is set at 3.5 m/s, the atomizing nozzle velocity is set at 4.1 m/s, and the seed coating agent flow rate is 0.36 L/min, the particles are suspended due to air isolation, forming a spouted fluidized bed. It is good for seed and powder contact and rapid prototyping. In this time, the pelleting qualified rate was 95.8%. The results provide theoretical basis and technical support for the research of small irregular seeds pelletizing technology.

摘要
为了探究冰草种子与丸化粉料在丸化过程中的颗粒时空分布、运动状态以及寻找丸化预混合装置最优的进气速度，揭示丸化成型机理。基于Herz-Mindlin接触理论，建立了种粉丸化接触力学模型；采用CPFD软件对丸化预混合装置进行建模与仿真分析，分析颗粒间的接触、碰撞、摩擦规律。仿真与试验结果表明：随着风速增加床体膨胀升高，床体内单位体积颗粒浓度下降，而气压差仅略微增加，当入口风速设为 3.5 m/s、雾化喷头速度设为 4.1 m/s、种衣剂流量 0.36 L/min时，颗粒间因被空气隔离而悬浮，形成喷动式流化床，有利于种粉接触、快速成型，该风速下丸化合格率为 95.8%。研究结果为小粒不规则种子丸化技术的研究提供理论基础和技术保障。

INTRODUCTION
Seed pelleting technology is the use of specific powder through mechanical processing methods, made of uniform size, regular shape of small spheres. The core problem of pelleting technology is whether the particle size increases evenly. The seeds with increased particle size are conducive to mechanized precision sowing, increase the fluidity of seeds, and achieve the purpose of saving seeds and improving sowing efficiency (*Shao, 2018*). Therefore, high quality pelleting technology has become an urgent demand. In addition to the need of drought resistance, cold resistance, saline alkali resistance and soil borne diseases control, the diversification and functional specialization of grass seed pelleting has become a novel development trend (*Qiu, 2017*).

The function of pelleting premixer is to promote the full mixing of seed and powder, and its mixing effect is directly related to the quality of pelleting (*Jiang, 2019*). At present, domestic and foreign scholars have studied the motion law of materials in the drum and the mixing effect between materials (*Yang, 2003; Koteswara, 2013*). Christodoulou studied the hydrodynamic behaviour model of film coated suspension in the process of tablet coating (*Christodoulou, 2020*). Computational fluid dynamics (CFD) method was used to simulate the solid-liquid mixing process in stirred tank (*Xu, 2019*). Liu Wenjun used discrete element theory to simulate and analyse the mixing characteristics of materials in coal mine rotary kiln (*Liu, 2017*). Liu used discrete element method to simulate the radial mixing process and motion law of particles in U-mixer (*Liu, 2019*).

Hou Zhanfeng optimized the process parameters of vibration pelleting machine (*Hou, 2020*). Throughout the above research, it is found that the mixing between materials is a very complex physical behaviour, and the mixing uniformity cannot be expressed quantitatively.

Therefore, this paper designed a spouted fluidized bed Agropyron seeds pelleting premixer. The Agropyron seeds were suspended in the mixing chamber in a spouted fluidized bed, and the atomized pelleting agent was sprayed on the outer surface of the seeds to achieve the ideal pelleting effect.

MATERALS AND METHODS

Test Equipment

The spouted fluidized bed pelleting premixing device is mainly composed of gas predistribution chamber *10*, seed and liquid mixing chamber *7* and settling chamber *4*, as shown in Fig. 1.

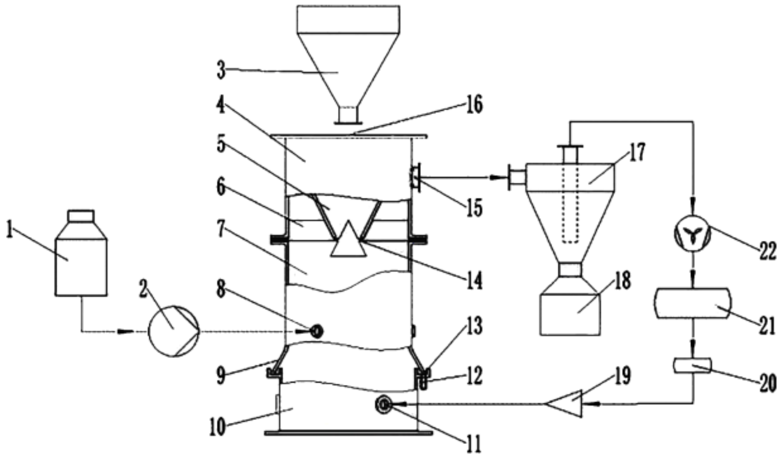


Fig. 1 - Pelleting pre-mixing equipment
Schematic diagram of overall structure of pelletizer for Agropyron seeds

1. Seed coating box; 2. Liquid supply pump; 3. Seed supply hopper; 4. Settling chamber; 5. Conical guide bucket; 6. Gas solid isolation plate; 7. Seed and liquid mixing chamber; 8. Adhesive supply port; 9. Liquid guide plate; 10. Gas predistribution chamber; 11. Air supply port; 12. Adhesive guide tube; 13. Annular seal; 14. Conical feeder; 15. Exhaust port; 16. Seed feeding port; 17. Dust removal device; 18. Recovery device; 19. Pressure relief valve; 20. Air purification device; 21. Air compression tank; 22. Air compressor

Working principle of spouted fluidized bed

As shown in Fig. 1, the purified air is compressed into the air compression tank *21* through the air compressor *22*, and then enters the gas predistribution chamber *10.* The seeds in the seed hopper *3* enter the conical guide bucket *5* through the seed feeding port *16*, and then enter the seed and liquid mixing chamber *7*. The adhesive in the seed coating box *1* is pressurized by the liquid supply pump *2* and then enters the seed and liquid mixing chamber *7*. With the increase of the air flow through the predistribution chamber *10*, the lifting force of the seeds in the seed and liquid mixing chamber *7* will also increase. When the lifting force received by the particles is just equal to their own weight, the particles will move violently in the bed to form fluidization. At this time, the adhesive is sprayed into the seed and liquid mixing chamber *7* through the adhesive supply port *8* to contact with the suspended seeds for adhesion. When the air flow continues to increase, the seeds will continue to rise to the gas solid isolation plate *6*, and the seeds collide with the spoiler to reduce the speed. At the same time, the air flow enters the settling chamber *4* after passing through the gas solid isolation plate 6, and then enters the seed feeding port *17* through the exhaust port *15*. Besides, the light weight seeds mixed in the air flow are collected into the recovery device *18* after passing through the cyclone separator. After mixing, the seeds fall into the coater for the next pelleting work.

NUMERICAL SIMULATION

Seed and powder contact mechanics model

During the pelleting process, when the outer surface of Agropyron seeds contacts with the adhesive, the interaction force between the seed and powder is far less than the adhesive force, which realizes the pelleting process. However, the interaction between the seed of Agropyron and powder during the rotation of the coater is mixing in most cases, and the next step of bonding will be conducted only after the mixture is even. In this way, the process of mixing and bonding is repeated until the ideal pelleting effect is achieved.

Based on Herz-Mindlin contact theory, it is assumed that the force between the seed and powder is a small deformation and recoverable collision force, that is, the impact force of the elastic sphere on the seed surface. The impact process of the powder particles and the Agropyron seeds is shown in Fig. 2.

In the discussion of contact problems, it is generally assumed that:

1. The contact system is composed of two objects in contact with each other, and there is no rigid body motion between them.
2. The deformation of the contact object is small, the contact point can be determined in advance, and the contact or separation is only carried out at the corresponding point where two objects may contact.
3. The medium of contact surface and the influence of dynamic friction are not considered.
4. The seeds were oval in shape and distributed evenly.
5. The powder is approximately a sphere with uniform size and mass distribution.

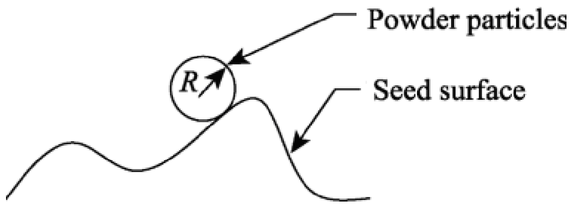


Fig. 2 - Figure of powder impact on seed surface

As shown in Fig. 2, the radius of the elastic ball is setting at R, and impacts the Agropyron seeds at the speed V. according to the Hertz contact theory, the penetration depth of the elastic ball impacting the seed surface is as follows:

$$\lambda = \left[\frac{9}{10}\frac{P^2}{R}E^2\right]^{\frac{1}{3}} \tag{1}$$

Therefore, the pressure P can be obtained as follows:

$$P = \frac{4}{3}E^{-1}R^{\frac{1}{2}}\lambda^{\frac{3}{2}} \tag{2}$$

$$\frac{1}{E} = \frac{1-{\mu_1}^2}{E_1} + \frac{1-{\mu_2}^2}{E_2} \tag{3}$$

Where: E_1, μ_1 and E_2, μ_2 are the elastic modulus and Poisson's ratio of the elastic ball and seed respectively.

According to Newton's second law:

$$m\frac{d^2\lambda}{dt^2} = -P \tag{4}$$

By substituting the calculated pressure P into the above formula and integrating λ, the following results can be obtained:

$$\frac{1}{2}\left[v^2 - (\frac{d\lambda}{dt})^2\right] = \frac{8}{15}\frac{R^{\frac{1}{2}}E}{m}\lambda^{\frac{3}{2}} \tag{5}$$

Where V is the initial velocity of the elastic ball impacting the seed. When the maximum impact velocity λ_1 is reached, $d\lambda/dt$ = 0. It is concluded that:

$$\lambda_1 = \left[\frac{5\pi}{4}\rho(\frac{1-{V_1}^2}{E_1} + \frac{1-{V_2}^2}{E_2})^{\frac{2}{5}}\right]^{\frac{2}{5}} RV^{\frac{4}{5}} \tag{6}$$

At this time, the maximum load P_1 between seed and powder is:

$$P_1 = \frac{4}{3}(\frac{5\pi}{4}\rho)^{\frac{2}{5}}(\frac{1-{V_1}^2}{E_1} + \frac{1-{V_2}^2}{E_2})^{\frac{-3}{5}} R^{\frac{3}{2}}V^{\frac{6}{5}} \tag{7}$$

Where: ρ - density of elastic sphere, [kg/m^3];

At this time, increasing the impact force can improve the turbulence degree of powder flow. The impact force can be expressed as:

$$P_1 = m_1 \frac{V'_1 - V_1}{t} = m_2 \frac{V'_2 - V_2}{t} \tag{8}$$

Where: V_1, V_1', V_2, V_2' - the velocities of seeds and powders before and after collision, [m/s].

It can be seen that the impact force is mainly related to the speed difference from equation (8). Therefore, the introduction of pelleting premixing chamber can increase the speed difference between the seed and powder, promote the seed and powder to "boiling" state, and improve the pelleting quality of pelleting seeds.

Simulation analysis of premixing chamber

Model import and mesh generation

The premixing chamber model established in Creo software is imported into CPFD simulation software, and the imported model is meshed. The number of meshing is 150000. Because the finer the meshing is, the higher the accuracy of simulation is. Therefore, under the condition of ensuring the processing speed, the number of meshing is set higher, as shown in Fig. 3.

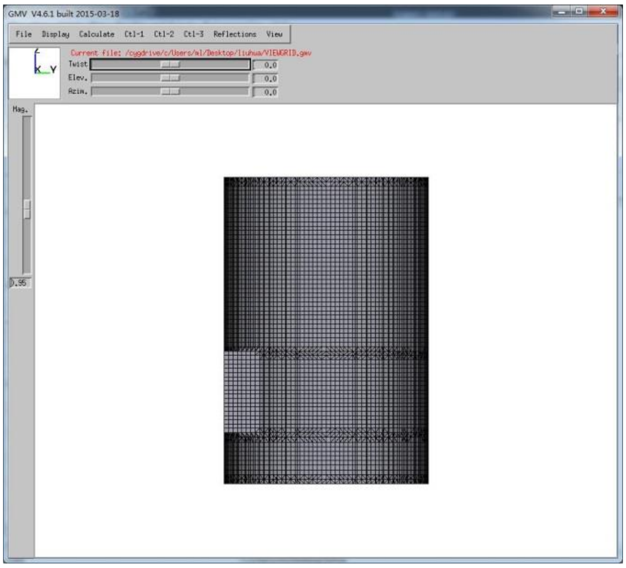
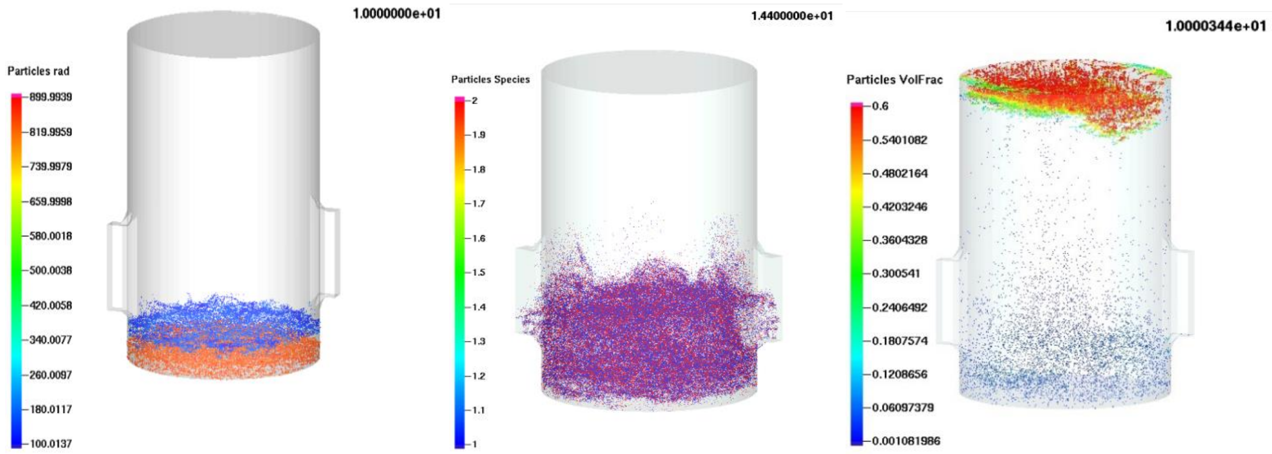


Fig. 3 - Mesh generation

Simulation results analysis of powder mixing

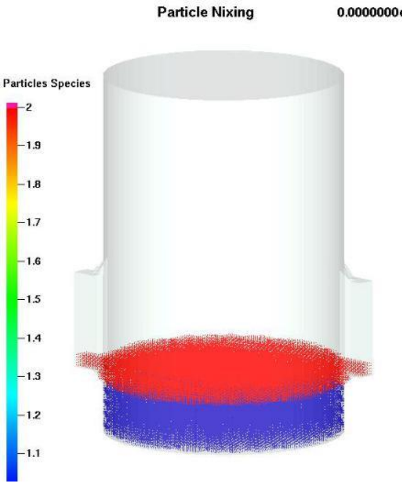
In order to study the mixing of Agropyron seeds and powder in premixing chamber under different inlet wind speed, the temporal and spatial distribution of Agropyron seeds and powder were studied. When the inlet wind speed is set at 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s, 2.5 m/s, 3 m/s, 3.5 m/s, 4 m/s, 4.5 m/s and 5 m/s, the temporal and spatial distribution of particles is shown in Fig. 4. The orange particles in the figure are pelleting powder, and the blue particles are Agropyron seeds.



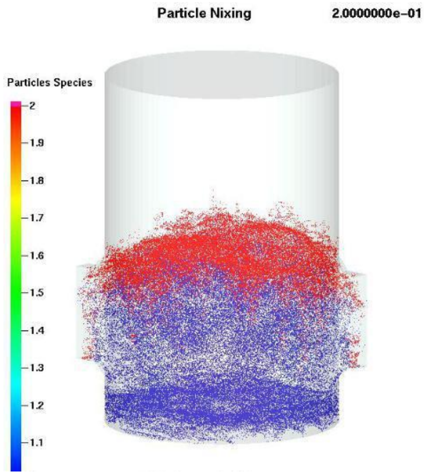
a. Particle distribution at inlet wind speed of 0.5m/s *b. particle distribution at inlet wind speed of 3.5m/s* *c. Particle distribution at inlet wind speed of 5 m/s*

Fig. 4 - Contrast diagram of particle distribution in different inlet wind speed

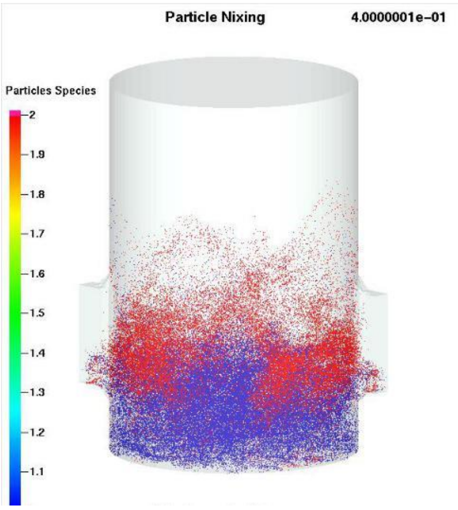
In order to determine the optimal inlet wind speed, three kinds of wind speed were selected from the set 9 kinds of wind speed to study the temporal and spatial distribution of particles. The inlet wind speed was 0.5m/s, 3.5 m/s and 5m/s respectively. As shown in Fig. 4a, when the inlet wind speed is 0.5 m/s, the movement between Agropyron seeds and powder is not obvious, and it is difficult to roll, jump and disperse. The mixing effect of pelleting is poor. However, when the wind speed is 3.5 m/s in Fig. 4b, the movement of particles is more intense, and the particles are in a "boiling" state, which increases the chances of contact, collision, friction and rolling between Agropyron seeds and powder, which is conducive to improving the pelleting quality. Besides, Fig. 4c shows the distribution of particles when the inlet wind speed is 5 m/s. It can be seen that too high inlet wind speed will cause most particles to concentrate on the top of the premixing chamber, which is not conducive to the mixing of Agropyron seeds and powder. The space utilization rate of the premixing chamber is poor, resulting in the increase of multi-seed rate and seedless rate, and the decrease of pelleting qualified rate. Therefore, the initial simulation results show that when the inlet speed is 3.5 m/s, the mixing effect of Agropyron seeds and powder is better, and can reach the ideal premixed state.



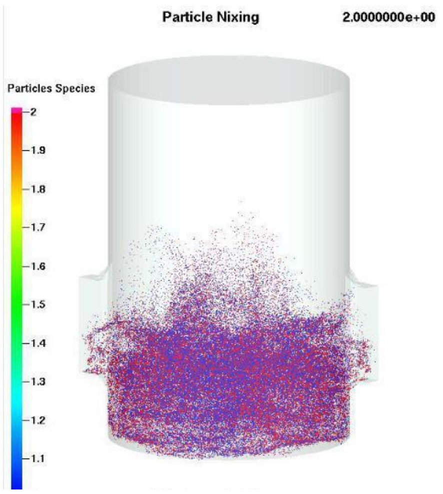
a. Particle distribution at 0 s



b. Particle distribution at 2 s



c. Particle distribution at 4 s



d. Particle distribution at 20 s

Fig. 5 - When the inlet wind speed is 3.5m/s, the distribution of particles in different times

Fig. 5a shows the initial state of Agropyron seeds and powder in simulation 0 s. The seeds of Agropyron seeds and powder are independent of each other when they are put into the premixing chamber initially, and they have obvious moving boundary, so it is difficult to achieve the ideal mixing state. Fig. 5b shows the temporal and spatial distribution of Agropyron seeds and powder when the simulation time is 2 s. It can be seen from this process that the moving boundary between Agropyron seeds and powder is shrinking, and there is a relative moving trend. This process is the initial state of particle mixing. Fig. 5c shows the state of population movement when the simulation duration is 4 s. Under the action of air flow, there is an obvious relative movement trend between Agropyron seeds and powder, which is conducive to the good mixing of Agropyron seeds and powder. Fig. 5d shows the population distribution when the simulation duration is 20s.

At this moment, the population has formed a good solid fluidized bed under the action of pneumatic force, which can achieve the ideal purpose of seeds and powder mixing, and is conducive to improving the qualified rate and quality of Agropyron seeds pelleting.

RESULTS AND DISCUSSION

Orthogonal test

Taking the pelleting qualified rate as the test performance index, taking the inlet wind speed, atomizing nozzle velocity and seed coating agent flux as the test factors, the orthogonal test with 3 factors and 3 levels was conducted. The factor level code is shown in Tab. 1.

Table 1

Factors and levels encode table

Level	Inlet wind speed A/ [m/s]	Atomizing nozzle velocity B/ [m/s]	Seed coating agent flux C/ [L/min]
1	2.5	2	0.25
0	3.5	4	0.35
-1	4.5	6	0.45

Each group of tests were conducted 3 times, with an interval of 10 min, and the average test results were taken. Take three samples randomly from each test sample, and observe them with a 5-fold magnifying glass. Then separate out the completely coated seeds of Agropyron and determine them as qualified for pelleting. Calculate the pelleting qualified rate according to formula (9) and then take the average value. The statistical results are shown in Tab. 2.

$$J = \frac{Z_d}{Z_d + Z_f} \times 100\% \tag{9}$$

In formula (9), J-the pelleting qualified rate, [%];

Z_d - the number of seeds completely coated Agropyron seeds, [-];

Z_f - the number of seeds of incompletely coated Agropyron seeds, [-];

Table 2

Quadratic regression orthogonal test scheme and experimental results

Test No.	Inlet wind speed A [m/s]	Atomizing nozzle velocity B [m/s]	Seed coating agent flux C [L/min]	Pelleting qualified rate [%]
1	0	0	0	84.2
2	-1	-1	0	75.1
3	0	1	-1	76.5
4	0	0	0	83.9
5	0	0	0	83.8
6	-1	0	-1	76
7	1	1	0	75.6
8	1	0	-1	76.5
9	0	-1	-1	75.9
10	0	0	0	84.1
11	-1	1	0	73.2
12	0	1	1	76.2
13	0	0	0	83.7
14	0	-1	1	74.9
15	1	0	1	76.8
16	1	-1	0	76.5
17	-1	0	1	75.8

Analysis of pelleting qualified rate

According to the quadratic regression orthogonal test scheme and test data in Tab. 2, the quadratic regression method was used to analyse the pelleting qualified rate. First, Design-expert was used for variance analysis (see tab. 3) and the regression mathematical model was established.

$$J=95.62+1.24A+0.14B-0.56C+0.075A \bullet B-0.025A \bullet C-0.050B \bullet C-1.43A^2-1.91B^2-1.55C^2 \tag{10}$$

A is the inlet wind speed, [m/s]; B - the atomizing nozzle velocity, [m/s]; C - the seed coating agent flux, [L/min].

The absolute value of each factor in the regression mathematical model determines the influence on the pelleting qualified rate. Therefore, the influence of each factor on the pelleting qualified rate can be determined by the regression model as inlet wind speed > seed coating flux > atomizing nozzle velocity.

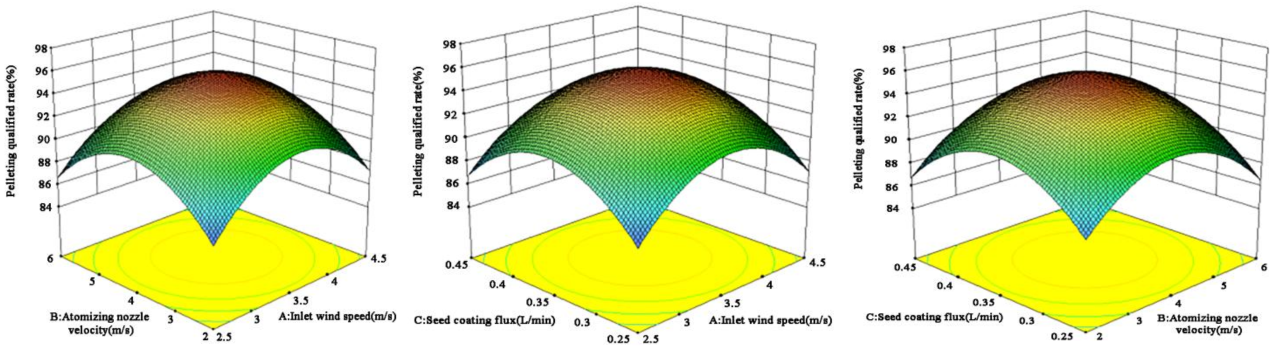
Table 3

Variance analysis of test result of pelleting qualified rate

Origin	Squares	Df	SD	F Value	P Value
Mode	273.894	9	30.433	202.788	**
A	0.911	1	0.911	6.072	**
B	0.001	1	0.001	0.008	
C	0.125	1	0.125	0.833	*
A•B	0.090	1	0.090	0.600	*
A•C	0.063	1	0.063	0.416	
B•C	0.202	1	0.202	1.349	*
A^2	82.818	1	82.818	551.856	**
B^2	80.961	1	80.961	539.483	**
C^2	80.040	1	80.040	533.349	**
Residua	1.365	7	0.195		
Lack of Fit	0.313	3	0.104	0.396	
Pure Error	1.052	4	0.073		
R^2	0.9669				
Adequate Precision	11.362				

The *F* value of the model is 202.8 and the *P* value is less than 0.01 in tab. 3. The *P* value of the model is extremely significant and the mismatch term is not obvious, which proves that the regression equation (10) has high fitting accuracy with the actual results. Therefore, the model can be used to analyse and predict the pelleting qualified rate.

According to the regression mathematical model (10), the response surface of inlet wind speed, seed coating agent flux and atomizing nozzle velocity to the pelleting qualified rate was obtained (Fig. 6).



a) J=(A,B,0) b) J=(A,0,C) c) J=(0,B,C)

Fig. 6 - Response surface of pellet rate

According to the corresponding surface of pelleting qualified rate, with the increase of inlet wind speed, pelleting qualified rate first increases and then decreases. With the increase of atomizing nozzle velocity, pelleting qualified rate first increases and then decreases. With the increase of seed coating flux, pelleting qualified rate first increases and then decreases.

Optimisation and experimental verification

According to the fitting factor and response value of quadratic regression equation, the optimal parameters were obtained by using Design-expert software.

$$\begin{cases} \max J \\ 2.5 \le A \le 4.5 \\ 2 \le B \le 6 \\ 0.25 \le C \le 0.45 \end{cases} \tag{11}$$

Through the analysis of Design-expert software, when *A*=3.5, *B*=4.1, *C*=0.36, the optimal value *J*= 95.8%, that is, when the inlet wind speed is 3.5 m/s, the atomizing nozzle velocity is 4.1 m/s, and the seed coating flux is 0.36 L/min, the pelleting qualified rate is 95.8%.

CONCLUSIONS

1) The law of contact, collision and friction between Agropyron seeds and powder in pelleting process was analysed theoretically, and the pelleting mechanism was revealed.

2) CPFD software was used to model and simulate the premixing chamber. The results showed that with the increase of inlet wind speed, the bed expansion increased, the particle concentration per unit volume in the bed decreased, while the pressure difference only increased slightly. When the inlet wind speed reached 3.5 m/s, the particles suspended due to air isolation, forming a spouted fluidized bed, which was conducive to seeds and powder contact and rapid prototyping.

3) Response surface methodology was used to analyse the test, and the main and secondary factors affecting the pelleting qualified rate of Agropyron seeds were determined as inlet wind speed > seed coating flux > atomizing nozzle velocity. When the inlet wind speed was 3.5 m/s, atomizing nozzle velocity was 4.1m/s, and seed coating flux was 0.36 L/min, the pelleting qualified rate was 95.8%.

ACKNOWLEDGEMENTS

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