RESEARCH ON THE ANTI-CRUSHING MECHANISM OF CORN GRAIN PNEUMATIC CONVEYING PROCESS UNDER THE INFLUENCE OF MULTI-PARAMETER COUPLING

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多参数耦合影响的玉米颗粒气力输送过程抗破碎机理探究

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ABSTRACT

In order to reduce the crushing rate and energy consumption of corn kernels in the pneumatic conveying process, this paper firstly used the conveying wind speed, material-air ratio and corn kernel moisture content as the influencing factors in the conveying process to conduct single-factor simulation experiments. Then, a test platform was created for the pneumatic conveying of grain particles and an orthogonal test was conducted using the crushing rate and pipeline pressure drop as conveying performance indices. A regression equation model was then created that connected each test index to each factor in turn. Lastly, it was used the response surface method for multi-objective optimization to determine the ideal parameter combinations for the conveying wind speed, which was 25.42 m/s, the material to gas ratio, which was 10, and the moisture content, which was 13.912%. At this time, the corresponding pneumatic conveying indexes are 1.112% crushing rate, 8.725 kPa pressure drop, and 0.328 kg/s conveying capacity, which provide theoretical and experimental bases for the prevention of crushing and the reduction of energy consumption during the pneumatic conveying of grain particles.

摘要

为降低玉米籽粒在气力输送过程中的破碎率、减小能耗，本文将输送过程中输送风速、料气比和玉米籽粒含水率作为影响因素分别进行单因素仿真实验，然后，设计并搭建粮食颗粒气力输送试验平台，以破碎率和管道压降为输送性能指标进行正交试验，分别建立起各试验指标与各因素之间的回归方程模型，最后，利用响应面法进行多目标优化，得到最优参数组合为输送风速为 25.42m/s，料气比为 10，含水率为 13.912%。此时对应的气力输送指标分别为破碎率为1.112%，压降为8.725kPa，此时的输送能力为0.328kg/s。为粮食颗粒气力输送过程防破碎和降低能耗提供理论和试验依据。

INTRODUCTION

Pneumatic conveying is a high-efficiency, flexible process arrangement, airtight environmental protection, safe, and reliable conveying method that is widely used in the storage of grain particles in logistics as well as in various aspects of the production and processing of food, feed, and industrial raw materials. Agricultural materials are widely used in the production and processing of food, feed, and industrial raw materials. Particle crushing is a necessary component of pneumatic conveying technology because of the inevitable collision behavior of particles and pipe walls. Therefore, the study of the interaction behavior between the particle motion distribution and the flow field in the gas-solid two-phase interaction process is a must to reveal the mechanism of corn grain crushing and reduce energy consumption.

The crushing properties of grain particles are influenced by a variety of variables. It is challenging to learn about the microscopic dynamics of a pneumatic conveying system by experimentation alone. For analyzing gas-solid two-phase flow, computational fluid dynamics with discrete element coupling is the best method. Hall studied the impact test that was carried out under the same conditions, the degree of damage depended on the type of grain, which was tested for wheat, rice, soybeans and corn, and corn was the most prone to breakage, followed by soybeans (*Hall et al,1974*). Kendall found that large grains are more likely to be damaged than small grains (*Kendall K.,1978*).

The reason is that when the particles are small, the stress required for crack propagation increases. At the same time, larger grains have larger mass, so they are subjected to greater impact force during the impact process. Chen conducted compression, friction and repeated impact tests on corn grains and wheat respectively, and the results showed that corn grains and wheat were sensitive to compression and impact loads, and friction brought little damage to these two grains, and both of them had good anti-wear ability (*Chen et al, 2021*). Shamba studied wheat and rye seeds and found that when the water content is below a certain limit, the damage sensitivity decreases with the increase of grain water content (*Shahbaz et al, 2012*). Grains with low water content are more likely to be broken, because they are more brittle, less elastic and have lower fracture energy than grains with high water content. Su measured the physical mechanics of different types of corn grains and studied the damage resistance and compression characteristics of bulk corn through compression experiments on bulk corn (*Su et al, 2019*). It was found that when the water content increased from 12% to 31%, the crushing rate, maximum shape variable and deformation energy of corn grains all increased, while the hardness decreased with the increase of water content. Salman used a continuous airflow gun to take fertilizer particles as the experimental material, and experimentally studied the effects of impact angle, impact velocity and impact frequency on the breakage rate of single particles (*Salman et al, 2002*). It was found that when the impact angle is larger, a smaller impact velocity leads to a higher crushing rate, and when the impact angle is smaller, increasing the number of impacts does not lead to a higher crushing rate, and it was also found that an increase in particle size leads to a sharp increase in particle crushing rate. A small impact velocity will lead to a higher crushing rate. The study found that when the impact angle is small, increasing the crushing frequency will not lead to an increase in the crushing rate. At the same time, it was found that increasing the particle size will lead to a sharp increase in the crushing rate.

However, all of these efforts have looked at one factor at a time. The combined effect of multiple factors is ignored. Peng conducted an experimental study on the collision process between the larvae of the black water fly and the wall, and analyzed factors such as collision material, falling height, material thickness, collision angle, falling direction, and water content, and concluded the relationship between the larvae of the black water fly and the above factors (*Peng et al, 2021*). Liu used high-speed photography technology combined with three-dimensional dynamic coordinates to analyze the collision process of oil sunflower seeds, and established regression equations of falling height, material thickness, collision angle, water content and recovery coefficient (*Liu et al, 2020*). The conventional orthogonal design technique is a mathematically based design approach that may determine the optimal arrangement of various component levels. But because orthogonal design can only be used to evaluate discrete data, it has limited precision and unpredictable results. The response surface approach may create a high-precision regression equation using a nonlinear model, make accurate predictions, and identify the ideal process conditions. As a result, employing the response surface approach to examine the variables impacting corn crushing rate is more trustworthy.

In summary, the single factor analysis of the three factors which affect the crushing rate of maize was carried out. Secondly, a multi-bend pneumatic conveying platform for grain particles was built. Finally, by synthesizing the influence of different factors on particle breakage and pipeline pressure drop, the influence of different factors on the crushing rate and pipeline pressure drop is obtained, and the influence law and principle are analyzed. The response surface method is adopted to comprehensively analyze the influence of each factor, and the optimal parameter ratio is obtained. The reliability of the multi-objective optimization model is verified, which provides theoretical and experimental basis for preventing crushing and reducing energy consumption during the pneumatic conveying of grain particles.

MATERIALS AND METHODS

System architecture

Based on the findings of the investigation into the relationship between corn kernels and the flow field in the pipeline, an experimental platform for pneumatically conveying grain particles in conjunction with curved pipe was constructed in order to examine the influence law of various factors on the effect of pneumatic conveying of corn kernels. As shown in Fig.1, the experimental platform for positive pressure pneumatic conveying of grain particles is mainly composed of Roots blower, vortex flowmeter, rotary unloader, hopper, frequency converter, cyclone separator, glass sight glass, pressure transducer, signal acquisition system, high-speed camera and PLC control cabinet. The Jinkong JGR-80H Roots blower supplies the air for the experimental platform. It has a rated flow rate of 3.07 m3/min, a rated power of 7.5 kw, and a pressure range of 0–63.7 KPa. The conveying wind speed can be controlled and measured by measuring the air flow with a vortex flowmeter.

Vortex flowmeter being connected to the air inlet of the rotary unloader, corn kernels and other food particles can be fed through the hopper on the rotary unloader, through the rotating unloader uniformly into the gas-solid injector, the material in the gas-solid injector and the airflow is fully mixed, with the conveying airflow into the initial section of the straight tube for acceleration. In order to avoid the effect of different wall materials at bend on the test results, it was chosen to connect a better wear-resistant glass pipe sight glass before and after the 180° bend, and measure the particle velocity with a high-speed camera to record the particle movement before and after the bend. In order to study the flow characteristics more comprehensively, the test platform is designed with multiple 180° bends to realize long-distance conveying tests in the laboratory space. Corn kernel is transported in the pipe under the action of conveying airflow, and then finally the cyclone separator is used to separate the gas and solid and collect the materials.

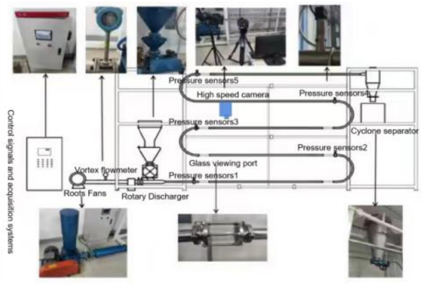
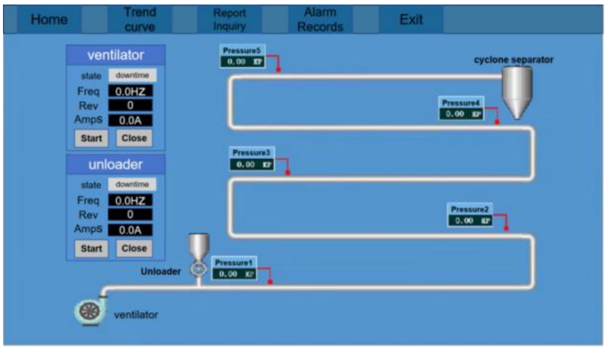


Fig. 1 - Multi-bend Pneumatic Conveying Test Platform for Grain Pellets

Control and signal acquisition system test equipment

The control and signal acquisition system of this test platform is mainly composed of pressure sensor, vortex flow meter, frequency converter, PLC control cabinet and dynamic signal measurement and control system. The model of the pressure sensor is Lester LST-131 diaphragm sheet pressure sensor made of diffusion silicon, powered by 24V DC power supply, and the range of the pressure sensor is 0-100kPa. With the change of the airflow pressure in the pipeline, the pressure sensor outputs a 4-20 mA current signal corresponding to the pressure of the airflow, and the pressure sensors 1 to 5 are distributed in different positions of the pipeline, as shown in Fig. 1. The output signals of the experimental process are transmitted to the self-developed dynamic signal measurement and control system through the signal acquisition instrument, and the main interface of the system is shown in Fig. 2. The vortex flowmeter is PFT-LUGB-2305-N vortex flowmeter, with a nominal diameter of DN50, nominal pressure of 1.6 MPa, accuracy of 1.5 grade, and a measurable flow range of 30-300 m^3/h.



ventilator
state downtime
Freq 0.0HZ
Rev 0
Amps 0.0A

unloader
state downtime
Freq 0.0HZ
Rev 0
Amps 0.0A

Pressure5 0.00 KP
Pressure4 0.00 KP
Pressure3 0.00 KP
Pressure2 0.00 KP
Pressure1 0.00 KP

Fig. 2 - Dynamic signal measurement and control systems

Experimental program

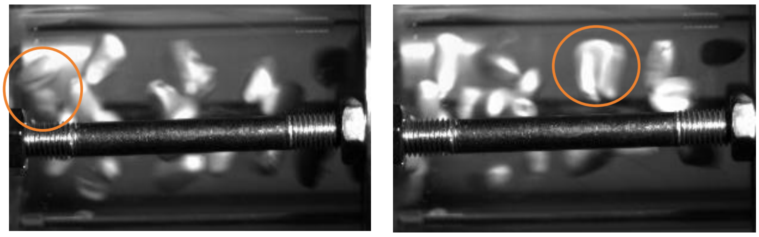
First, fix the bend pipe on the test stand, make good connections and check the sealing ring status, then, open the dynamic signal measurement and control software, adjust the frequency converter connected to the Roots fan and the frequency converter connected to the unloader to the required experimental settings; when the Roots fan enters into a stable conveying state, the vortex meter shows that the flow rate is the same as the expected conveying wind speed, add prepared corn kernels to the hopper; use the high-speed camera to record the movement status and position distribution in the pipe before and after entering the bend pipe; finally, re-sieve the broken kernels after conveying and save the pressure signal data. Use high-speed camera to record the movement of corn kernels before and after entering the pipe and the position distribution in the pipe; finally, the pressure signal data was saved and the conveyed corn grains were re-screened to screen out the broken corn grains and weighed. The morphology of the broken corn grains is shown in Fig. 3.

Fig. 3 - Example of corn kernel breakage

RESULTS

Particle motion analysis

A high-speed video camera was used to film the movement of corn kernels in the pipe and to analyze the average particle velocity before and after the bend. Measure the position of a particular corn kernel at time $t(x_t,y_t)$, as shown in Fig. 4(a), the position of the grain (x_{t+5},y_{t+5}) at the moment $(t+5)$ after 5 frames is measured, as shown in Fig. 4(b), and the distance between these two positions divided by the time of 5 frames is obtained as the moving speed of this corn kernel. In the conveying process every 1000 frames randomly selected 5 corn kernels to record the particle moving speed, a total of 5 groups of average speeds were recorded and the experimental data are shown in Table 1.



a) moment t b) moment t+5

Fig. 4 - Corn kernel grain movement

Analysis of pressure drop test results

The static pressure signals of the four pressure sensors in the flow field of the conveyor pipe, corresponding to the pressure signals of the four pressure sensors are shown in Fig.5. When the material enters the conveying pipeline, the pressure inside the pipeline will rise significantly as the material passes through, the values of the pressure sensors are recorded, and the pressure drop between different points can be calculated by calculating the difference between them. The variation of conveyed energy consumption under different test conditions can be obtained by recording the pressure drop between pressure sensors 1 and 4.

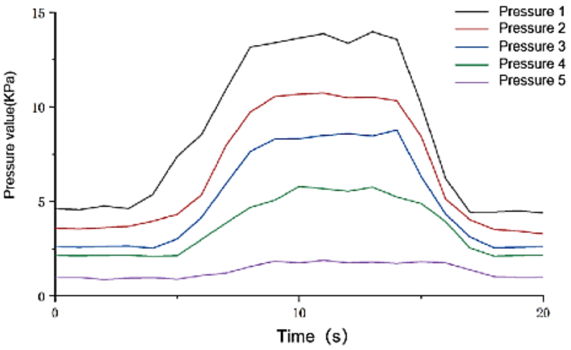


Fig. 5 - Pressure signal diagrams for different measurement points

Response surface method test results and analysis

The conveying air speeds of the corn kernels were selected as 25 m/s, 29 m/s and 33 m/s, the material-air ratios were controlled by the frequency conversion of the unloader, and the selected material-air ratios were 6, 8 and 10. The moisture contents of the corn kernels were 10%, 12% and 14%. The specific test coefficients and levels are shown in Table 1.

Table 1

Combined elbow pneumatic conveying test factors and levels

Level	Factor		
	Conveying wind speed （m/s）	Material-to-gas ratio	Moisture content （%）
-1	25	6	10.0
0	29	8	12.0
1	33	10	14.0

Desing-Expert software was utilized to create orthogonal tests in accordance with the Box-Behnken model, taking into account the orthogonal design elements indicated in Table1. Approximate experiments on the conveying process were conducted using the pneumatic conveying platform for grain particles, and the crushing rate and pipeline pressure drop under various parameter combinations were computed. The outcomes were displayed in Table 2. Each index findings in the table were calculated by averaging the outcomes of three separate, repeated experiments.

Table 2

Design of the orthogonal tests

Serial Number	Factor			Crushing rate Y_1	Pipe pressure drop Y_2
	Conveying wind speed X_1	Material-to-gas ratio X_2	Moisture content X_3		
1	-1	-1	0	1.495	6.62
2	1	1	0	4.705	15.31
3	0	0	0	2.885	9.64
4	1	0	1	4.596	13.97
5	0	0	0	2.831	9.78
6	-1	0	1	1.112	7.6
7	1	0	-1	5.437	13.53
8	-1	1	0	1.243	8.41
9	0	1	1	2.383	11.26
10	-1	0	-1	1.561	7.61
11	1	-1	0	5.143	11.95
12	0	-1	1	2.752	7.91
13	0	0	0	2.794	9.86
14	0	1	-1	3.285	10.37
15	0	-1	-1	3.328	7.52

Regression Equation for Crushing Rate

Table 3 shows that X_1, X_2, X_3, X_1X_3, and X_{12} are extremely significant at the α = 0.05 level. The regression equation between crushing rate Y_1 and the factors was obtained as shown in equation (3):

$$Y_1 = 2.84 + 1.81X_1 - 0.138X_2 - 0.346X_3 - 0.098X_1X_3 - 0.082X_2X_3 + 0.274X_1^2 \tag{3}$$

Table3

Variance analysis of crushing rate regression equation

Source	Mean Square	df	Sum of Squares	F Valve	p Valve
Model	27.64	9	3.07	588.84	< 0.0001**
X_1	26.17	1	26.17	5017.83	< 0.0001**
X_2	0.1518	1	0.1518	29.10	0.003**
X_3	0.9577	1	0.9577	183.62	< 0.0001**
X_1X_2	0.0086	1	0.0086	1.66	0.2542
X_1X_3	0.0384	1	0.0384	7.37	0.0421*
X_2X_3	0.0266	1	0.0266	5.09	0.0705
X_1^2	0.2786	1	0.2786	53.4	0.008**

Source	Mean Square	df	Sum of Squares	F Valve	p Valve
X_2^2	0.0046	1	0.0046	0.875	0.3924
X_3^2	0.0157	1	0.0157	3.01	0.1435
Residual	0.0261	5	0.0052		
Lack of Fit	0.0219	3	0.0073	3.48	0.231
Pure Error	0.0042	2	0.0021		
Cor Total	27.67	14			

Pipe pressure drop regression equation

The R^2=0.997>0.8 of the pipeline pressure drop regression model derived from this multifactor calculation indicates that the regression equation can better reflect the actual situation and the degree of fit is excellent. Adjustment $Radj^2$=0.993 and prediction $Rpre^2$=0.962 are basically consistent with each other, the difference between the two is within 0.2, indicating that the regression model is more accurate.

In Table 4, and it can be seen that X_1, X_2, X_3, X_1X_2, X_{12} are extremely significant at the level of α = 0.05. The P value greater than 0.1 indicates that the item of the model is not significant, the reduction of these items in the degree of influence and trend analysis will help to improve the model. After removing the insignificant terms with P-value greater than 0.1, the regression equation between the pipe pressure drop Y_2 and the factors was obtained as shown in equation (4):

$$Y_2 = 9.76 + 3.06X_1 + 1.42X_2 + 0.214X_3 + 0.393X_1X_3 + 1.11X_1^2 - 0.3X_3^2 \tag{4}$$

Table 4

Variance analysis of pipe pressure drop regression equation

Source	Mean Square	df	Sum of Squares	F Valve	p Valve
Model	97.71	9	10.86	214.25	< 0.0001**
X_1	75.15	1	75.15	1483.05	< 0.0001**
X_2	16.10	1	16.10	317.77	< 0.0001**
X_3	0.3655	1	0.3655	7.21	0.0435*
X_1X_2	0.6162	1	0.6162	12.16	0.0175*
X_1X_3	0.0506	1	0.0506	0.9990	0.3634
X_2X_3	0.0625	1	0.0625	1.23	0.3173
X_1^2	4.57	1	4.57	90.18	0.0002**
X_2^2	0.3323	1	0.3323	6.56	0.0506
X_3^2	0.1404	1	0.1404	2.77	0.1569
Residual	0.2534	5	0.0507		
Lack of Fit	0.2286	3	0.0762	6.14	0.1432
Pure Error	0.0248	2	0.0124		
Cor Total	97.97	14			

The contribution of each factor to the indicator is shown in Table 5.

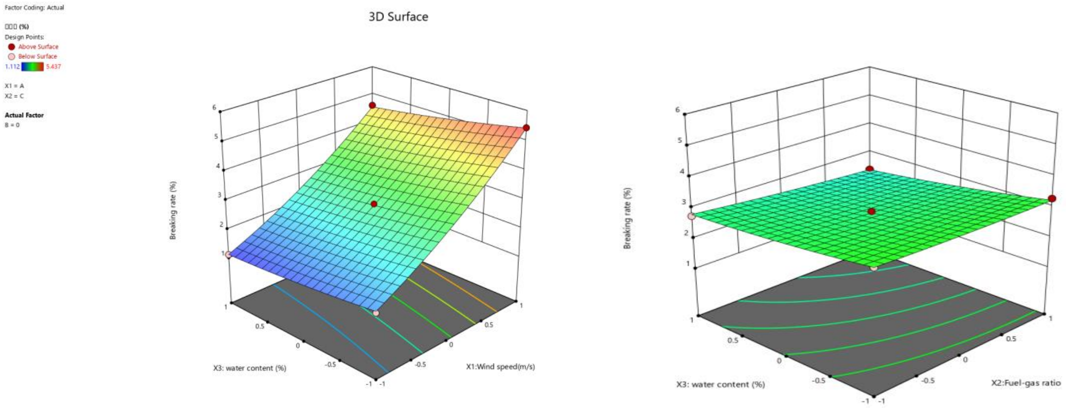
Table 5

Degree of influence of factors on indicators

Norm	Impact factor contribution rate								
	X_1	X_2	X_3	X1X2	X_1X_3	X_2X_3	X_{12}	X_{22}	X_{32}
Y_1	1.809	-0.138	-0.346	—	-0.098	-0.082	0.275	—	—
Y_2	3.065	1.419	0.214	0.393	—	—	1.113	-0.3	—
arrange in order	Y_1	X1>X3>X12>X2>X1X3>X2X3							
	Y_2	X1>X2>X12>X1X2>X22>X3							

Analysis of the influence law of each factor on the crushing rate

The one-way relationship between the crushing rate and each factor is negatively correlated with the water content and the material-gas ratio, except for the positive correlation with the wind speed. From the ANOVA results in Table 3, it can be seen that the p-value of conveying wind speed-water content (X_1-X_3) and material-gas ratio-water content (X_2-X_3) is <0.1, which is more significant to the crushing rate, in the above case, the Design-Expert software was used to draw the three-dimensional response surface analysis graphs of conveying wind speed-water content (X_1-X_3) and material-gas ratio-water content (X_2-X_3) on crushing rate. From Fig. 6(a), it can be seen that the crushing rate generated by the conveying wind speed is much greater than that by the moisture content; if the moisture content is small, the crushing rate with the wind speed changes faster, so in the design of grain particle pneumatic conveying system attention should be paid to conveying the lower moisture content of the particles to reduce the wind speed; from Fig. 4(b), it can be seen that the crushing rate is affected by the material-gas ratio and the water content, the material-gas ratio and water content (X_2 - X_3) on the three-dimensional response surface analysis. It can be seen from Fig. 6(b) that the crushing rate is affected by the ratio of material and gas and water content in a similar way, and the crushing rate is the smallest when the ratio of material and gas and water content are the largest.



(a) (b)

Fig. 6 - Crushing rate response surface analysis

Analysis of the influence pattern of each factor on pipeline pressure drop

From the ANOVA results in Table 5, it can be seen that the p-value of conveying wind speed - material-gas ratio (X_1-X_2) is <0.1, which has a more significant effect on the pressure drop of the pipeline. In the above case, the three-dimensional response surface analysis of conveying wind speed - material-gas ratio (X_1-X_2) on the pressure drop of the pipeline is plotted using Design-Expert software. From Fig. 5, it can be seen that the pipeline pressure drop by conveying wind speed is greater than by the influence of the material gas ratio, when the material-to-gas ratio is larger, the duct pressure drop varies more rapidly with the wind speed, that is, when the material gas is relatively large, the low air velocity will make the pipeline pressure drop up to too large, resulting in waste of energy consumption.

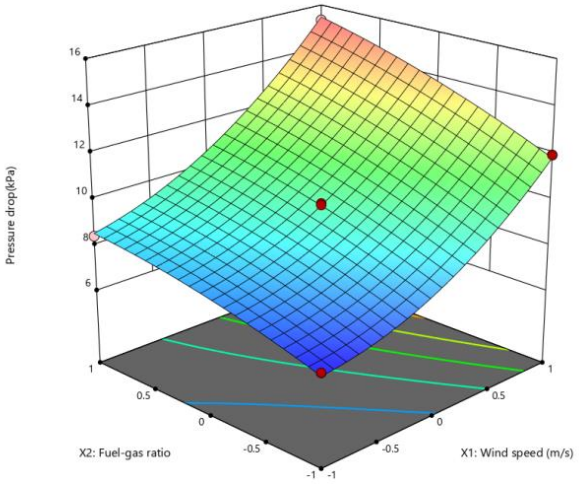


Fig. 5 - Pipeline pressure drop response surface analysis

CONCLUSIONS

In this paper, taking the minimum crushing rate, minimum pipeline pressure drop and maximum conveying capacity as the target, the three regression equation models established are used to do multi-objective optimization and solving, and the optimal parameter combinations are conveying wind speed of 25.42 m/s, material/gas ratio of 10, moisture content of 13.912%, and the corresponding pneumatic conveying indexes are 1.112% crushing rate, 8.725 kPa pressure drop, and 0.328 kg conveying capacity. The conveying capacity is 0.328 kg/s. The multi-objective optimization results were verified experimentally, and the indicators obtained from the verification were 1.143% crushing rate and 8.408 kPa pipeline pressure drop, and the relative error between the experimental value and the theoretical optimization value was within 8%, which verified the reliability of this multi-objective optimization model. In the process of corn grain conveying, controlling the conveying wind speed and material-air ratio can reduce the crushing rate of corn grains, reduce the energy consumption in the process of pneumatic conveying, so as to achieve the purpose of energy saving.

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