DESIGN AND EXPERIMENTAL STUDY OF EQUAL-AREA VARIABLE-PITCH SCREW STRUCTURE FOR WHEAT FLOUR

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小麦粉变距螺旋结构优化设计与试验研究

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ABSTRACT

The parameters of a wheat flour equal-pitch screw feeder are mainly based on empirical design. A method comparing the effect of the number of blocked zones on the feeding sections is proposed to complete the screw parameter of four feeding sections. According to the designed screw structure, Solid Works was used to build the three-dimensional model, and EDEM software was imported for discrete element analysis. It is found that the optimal solution is the screw design with two blocked zones, in which the cutting stock of the feeding sections is very uniform with high feeding accuracy on the premise of satisfying the screw feeding. In order to verify the rationality of the design of the screw structure, the screw was processed based on the optimal parameters, and the screw feeding device of the transparent outer cylinder was built with acrylic plate, and then the feeding stability of wheat flour was observed. The flow fluctuation of the designed screw is relatively small, and the feeding is more uniform, so the accuracy of the screw feed is higher. The experiment verifies the rationality of the variable pitch design and provides a reference for the design and development of wheat flour screw feeding device.

摘要

为提高小麦粉螺旋定量给料精度，针对等径变距螺旋主要以经验设计为主、缺乏系统设计方法的问题，提出基于进料段不同死区个数对称性分析设计的方法,并完成四种进料段螺旋结构参数设计。根据所设计的螺旋结构，利用 Soliworks 软件建立三维模型，导入 EDEM 软件进行离散元分析，存在两个死区的设计方案为最优的螺旋结构设计，此螺杆进料段下料均匀，在满足螺旋给料流量的前提下，给料精度高。为验证变距螺旋结构设计方法的合理性，根据最优参数加工螺杆，利用亚克力板搭建透明料筒的螺旋给料试验装置，分析小麦粉进料段下料稳定性。由检测结果可知，本文设计螺杆的流量波动相对较小，下料较为均匀，螺旋给料的精度较高，验证了变距螺旋结构设计的合理性，为小麦粉螺旋给料装置的设计研发提供参考。

INTRODUCTION

Screw feeders are widely used in the short-distance and high-precision feeding of bulk materials in food, chemical, agricultural and mineral processing industries. The main structure of the screw feeder includes three parts: bin, trough and screw. When the screw rotates, the material is drawn out from the hopper, and transported along the chute, and finally flows out from the discharge port. The screw feeder not only has good feeding accuracy control, but also can avoid environmental pollution caused by the material conveying process. However, when the powder is delivered through the screw feeder, it will fall in the hopper unevenly due to poor fluidity of powder, which results in mass flow fluctuation of screw feeding, uneven screw force and other problems. Most researchers use theoretical and experimental methods to study the flow law of materials in the screw feeder and the pressure drop of materials in the hopper. However, there are few researches on the design of screw feeder aimed at the stability of blanking in the hopper in the literature.

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Bates used different screws and materials to conduct matching experiments to study the flow laws (*Bates, 1969*). *Haaker et al*. also discussed theories for volumetric efficiency of screw feeders (*Haaker et al., 1993*). The theories were proposed based on deformation of bulk solid and on plug flow of bulk material. Experiments were conducted on a test rig and results were compared with prediction from the theories. Based on the theoretical model, *Yu* proposed a uniform flow pattern based on the characteristics of the screw pitch (*Yu, 1996*). *Roberts* use the pressure drop of the hopper material to predict the flow pattern generated in the hopper under a given screw (*Roberts et al., 1993a*). *Roberts and Manjunath* used these methods to analyze the volume reduction characteristics of the screw feeder in the hopper (*Roberts et al., 1993b*). Scholars have done a lot of research on the feeding uniformity of the hopper segment, but systematic research of its optimization is lacking (*Bates, 1969; Fernandez, 2011; Peng, 2017; Qiu et al., 2008; Zhang, 2006; Zhao and Yu, 2018*).

In order to improve the feeding stability of the screw feeder and the falling stability of the material in the hopper, a design method based on the symmetry analysis of the number of different dead zones in the hopper section is proposed, and four kinds of equal-diameter variable-pitch screw structures are designed. The 3D models are established by Solid Works software, and then introduced into EDEM software for discrete element analysis. It is found that the optimal design of the screw structure is the design of two dead zones, the feeding of the hopper section of the screw is uniform, and the feeding accuracy is high on the premise of satisfying the feeding flow of the screw. In order to further verify the rationality of the screw structure design and the reliability of the simulation, a wheat flour screw feeding experiment platform was built to carry out the experiment. The results show that the design of the variable pitch screw is reasonable, which provides a reference for the development and design of the wheat flour screw feeding device.

MATERIALS AND METHODS

Theoretical method

Each pitch of the equal-pitch screw feeder has the same conveyor capacity. In the hopper section, the front powder is pushed by the screw to fill the back space, so the back part cannot receive the powder in the hopper, resulting in the phenomenon of compaction (dead zone) (*Song, 1996; Su and Zhao, 1989; Yu, 1982; Gong, 1984*) of the powder in the hopper, thus affecting the precision of the screw feeding, as shown in Fig. 1.

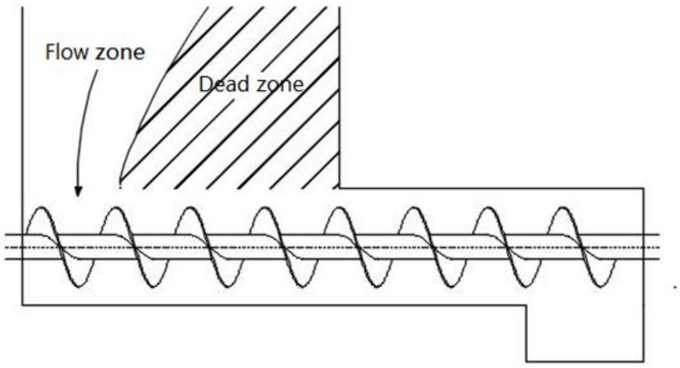


Fig. 1 - Equal pitch screw conveying

The length and structure of the screw in the hopper section are two main factors affecting the uniformity of feeding. This paper analyzes the structure of the screw in the hopper section with the uniform distribution of the dead zone and the flowing zone. As shown in Fig. 2, assume that the screw of the hopper section has a total of n pitch, denoted as S_1, S_2, S_3 and S_n. The number of turns corresponding to each pitch is k_1, k_2, k_3 and k_n. The dead zone is represented by A_1, A_2, A_3 and A_n. The first pitch for each pitch will always be the flowing area, while the last pitch will always be pushed forward to make a dead area above it.

So, we can know that:

$$A_1 = k_1 S_1,\quad A_2 = k_2 S_2,\quad A_3 = k_3 S_3 \cdots A_n = k_n S_n \tag{1}$$

$S_1, S_2, S_3 \ldots\ldots S_n$ are the pitch values of the screw feeding section, [mm];

$k_1, k_2, k_3 \ldots\ldots k_n$ are the number of turns corresponding to each pitch value;

$A_1, A_2, A_3 \ldots\ldots A_n$ are lengths of dead sections, [mm].

In order to ensure uniform feeding, the flowing zone and dead zone are symmetrically discussed, that is to guarantee:

$$A_1 = A_n,\ \ A_2 = A_{n-1},\ \ A_3 = A_{n-2}\cdots\cdots \tag{2}$$

For the feeding area, in order to ensure the uniform transition of the pitch, the arithmetic series principle is adopted between the pitch, so it can be known that:

$$S_2\text{-}S_1 = S_3\text{-}S_2 = S_4\text{-}S_3 = \cdots = S_n\text{-}S_{n-1} \tag{3}$$

The symmetry of the feeding area should be taken into account, so it can be known that $S_1 = S_n\text{-}S_{n-1}$. From this, the relationship between each pitch and the first pitch can be obtained:

$$S_2 = 2S_1,\ \ S_3 = S_1 + S_2 = 3S_1,\ \ S_4 = S_1 + S_3 = 4S_1 \cdots S_n = S_1 + S_{n\text{-}1} = nS_1 \tag{4}$$

If the total length of the feed section is L, the relationship between each pitch and the total length can be known as:

$$k_1S_1 + k_2S_2 + k_3S_3 + \ldots k_nS_n = L \tag{5}$$

L is the total length of the feed section, [mm].

According to the above assumptions and conclusions, the different situations of the number of dead zones A are discussed and analyzed in the following, so as to design and analyze the variable pitch structure of the feed section.

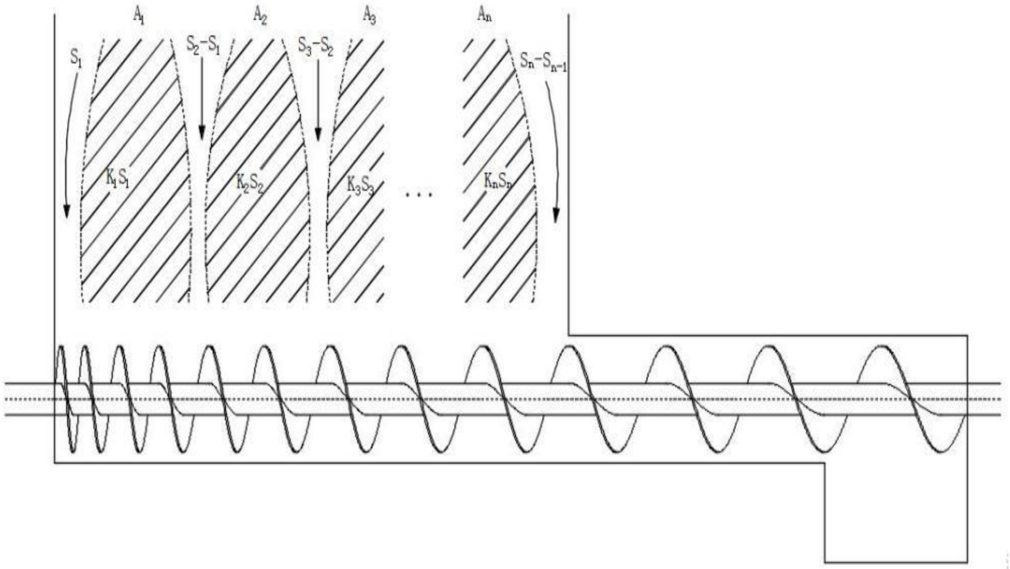


Fig. 2 - Equal diameter variable pitch screw

Single dead zone

When the dead zone $A=1$, two pitch are adopted for the design of the feeding section. In order to ensure uniform feeding, then:

$$k_1S_1 + S_2 = L$$

If $k_1 = 1$, then $L = 3S_1 \Rightarrow S_1 = \frac{L}{3}; S_2 = \frac{2L}{3}$.

If $k_1 = 2$, then $L = 4S_1 \Rightarrow S_1 = \frac{L}{4}; S_2 = \frac{1L}{2}$.

If $k_1 = 3$, then $L = 5S_1 \Rightarrow S_1 = \frac{L}{5}; S_2 = \frac{2L}{5}$.

If $k_1 = n$, then $L = (n+1)S_1 \Rightarrow S_1 = \frac{L}{(n+1)}; S_2 = \frac{2L}{(n+1)}$ (6)

The dead zone should be minimized to ensure uniform feeding. Therefore, $K_1 \leq 3$ is better for a dead zone.

Double dead zones

When the dead zone *A=2*, three pitches are adopted for the design of the feeding section. In order to ensure uniform feeding, then:

$$A_1 = A_2 \Rightarrow k_1S_1 = k_2S_2 \Rightarrow k_1 = 2k_2 \qquad (7)$$
$$k_1S_1 + k_2S_2 + S_3 = L$$

If $k_2 = 1$, $k_1 = 2$; then $L = 2k_1S_1 + S_3 \Rightarrow S_1 = \frac{L}{7}; S_2 = \frac{2L}{7}; S_3 = \frac{3L}{7}$.

If $k_2 = 2$, $k_1 = 4$; then $L = 2k_1S_1 + S_3 \Rightarrow S_1 = \frac{L}{11}; S_2 = \frac{2L}{11}; S_3 = \frac{3L}{11}$.

If $k_2 = 3$, $k_1 = 6$; then $L = 2k_1S_1 + S_3 \Rightarrow S_1 = \frac{L}{15}; S_2 = \frac{2L}{15}; S_3 = \frac{3L}{15}$.

The dead zone should be minimized to ensure uniform feeding. Therefore, it is better to take $K_1 \leq 4$ for the two dead zones.

Three dead zones

When the dead zone *A=3*, four pitches are adopted for the design of the feeding section. In order to ensure uniform feeding, then:

$$A_1 = A_2 \Rightarrow k_1S_1 = k_3S_3 \Rightarrow k_1 = 3k_3 \qquad (8)$$
$$k_1S_1 + k_2S_2 + k_3S_3 + S_4 = L$$

In order to ensure uniform feeding, the powder of the second dead zone should be as much as possible less than the first and third dead zones. Then:

$$k_1S_1 \geq k_2S_2 \Rightarrow k_1 \geq 2k_2 \qquad (9)$$

If $k_3 = 1$, $k_1 = 3$; then $L = 2k_1S_1 + k_2S_2 + S_4$.

The dead zone should be minimized to ensure uniform feeding, then $K_3 \geq 2$ and $K_1 \geq 6$ are not considered for the three dead zones.

From $K_1S_1 \geq K_2S_2 \Rightarrow K_1S_1 \geq 2K_2$, then $K_1S_1 \geq K_2S_2 \Rightarrow 3 \geq 2K_2 \Rightarrow K_2 \leq 1.5 \Rightarrow K_2 = 1$. So:

$$L = 2k_1S_1 + k_2S_2 + S_4 \Rightarrow S_1 = \frac{L}{12}; S_2 = \frac{L}{6}; S_3 = \frac{L}{4}; S_4 = \frac{L}{3} \qquad (10)$$

Four dead zones

When the dead zone *A=4*, five pitches are adopted for the design of the feeding section. In order to ensure uniform feeding, then:

$$A_1 = A_4 \Rightarrow k_1S_1 = k_4S_4 \Rightarrow k_1 = 4k_4,\ A_2 = A_3 \Rightarrow k_2S_2 = k_3S_3 \Rightarrow 2k_2 = 3k_3$$
$$k_1S_1 + k_2S_2 + k_3S_3 + k_4S_4 + S_5 = L \qquad (11)$$

If $K_4=1$, $K_1=4$; then $L=2K_1S_1+2K_2S_2+S_5$. The dead zone should be minimized to ensure uniform feeding, then $K_4 \geq 2$ and $K_2 \geq 6$ are not considered for the four dead zones.

From $K_2S_2=K_3S_3 \Rightarrow 2K_2=K_3$, then $K_3 \geq 4$ and $K_2 \geq 6$ are not considered, so:

$$L = 2k_1S_1 + 2k_2S_2 + S_5 \Rightarrow S_1 = \frac{L}{25}; S_2 = \frac{2L}{25}; S_3 = \frac{3L}{25}; S_4 = \frac{4L}{25}; S_5 = \frac{L}{5} \qquad (12)$$

When the dead zone *A=5*, the feeding section is designed with 6 pitches. In order to ensure uniform feeding, then $A_1=A_5 \Rightarrow K_1S_1=K_5S_5 \Rightarrow K_1=5K_5$. The pitch of the first turn S_1 should be at least five, but the dead zone is large, so the situation of the dead zone $A \geq 5$ is not considered.

Simulation experiment of screw feeding of wheat flour

The discrete element method can be used to conduct a comprehensive systematic study of the interaction between the powder and screw mechanism and the movement state of powder flow, but also can provide real-time monitoring of flow rate of screw feeder, material particle velocity distribution and stress distribution, which is convenient to make real-time contribution in accordance with the status of screw feeder. On this basis, screw parameters can be optimized to improve the speed and precision of wheat flour packaging, increase research and development efficiency and reduce the cost. In this paper, the feeding process of the screw feeder is simulated by using the EDEM software of the Altair (Shanghai) company.

Simulation model and parameters

Combined with related references, a three-dimensional model of screw conveyor is established by SolidWorks software of Dassault Systemes Company in France (*Rozbroj et al., 2015; Pezo et al., 2018; Orefice and Khinast, 2017*). The hopper height is 350 mm from the center line of the barrel; the caliber on the hopper is 300 mm long and 200 mm wide; the angle between the edge line of the lower mouth of the hopper and the end line of the barrel is 30 degrees, as shown in Fig. 3.

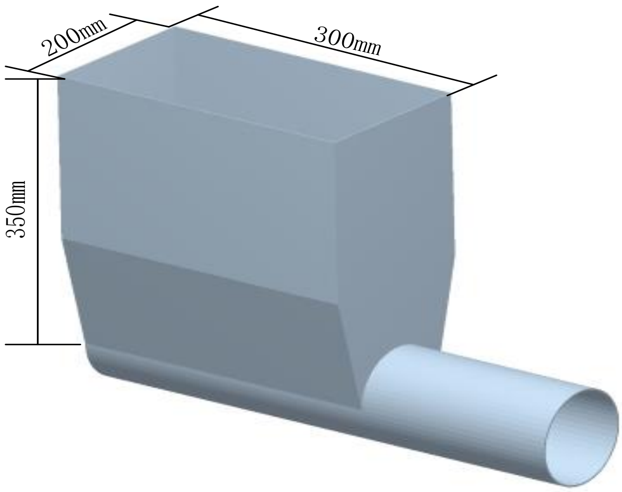
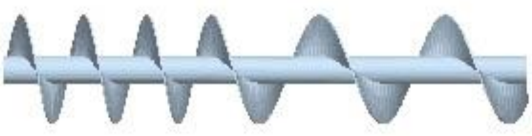
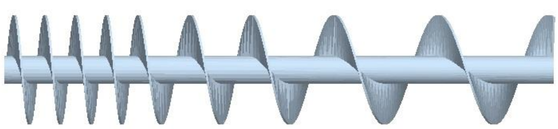


Fig. 3 - Three-dimensional model of the barrel

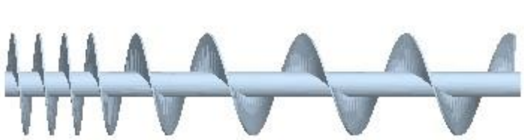
The outer diameter of the simulation screw blade is 100 mm. According to the size of the hopper, the length of the feeding section is 300mm. The screw is designed according to the method of considering the number of dead zones proposed. The three-dimensional models of the four types of screws below are constructed by Solid Works software. Their core size, blade diameter and the gap between the barrel wall and the blade are the same, except the structural parameters of the feed section of the screws. The three-dimensional model of the screw is shown in Fig. 4, and the structural parameters of the feeding section are shown in Table 1.



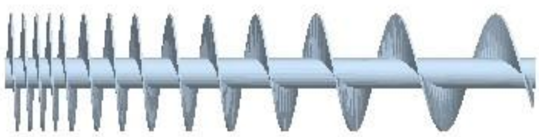
a. Single dead zone



b. Double dead zones



c. Three dead zones



d. Four dead zones

Fig. 4 - Three-dimensional model of four screws

In order to reduce simulation time, wheat flour particles were amplified to a radius of 1mm for simulation. Parameter calibration was completed based on the method of wheat flour parameter calibration in references *(Li et al., 2019*). The error between the simulation angle of repose and the actual value was less than 0.5%, and the wheat flour simulation parameters were obtained as shown in Table 2.

Table 1

Structural parameters of the four screw feed sections

The number of dead zones	Screw feeding section parameters (pitch × number of sections)
1	S1=60 mm x 3，S2=120 mm x 1
2	S1=27 mm x 4，S2=55mm x 2，S3=82 mmx1
3	S1=25 mm x 3，S2=50 mm x 1，S3=75 mm x 1，S4=100 mm x 1
4	S1=12 mm x 4，S2=24 mm x 3，S3=36 mm x 2，S4=48 mm x 1，S5=60 mm x 1

Table 2

Discrete element simulation parameter table of wheat flour enlarged particles

Simulation parameters	Value
Density of wheat flour/(kg·m^{-3})	1960
Poisson's ratio of wheat flour	0.2
Shear modulus of wheat flour/Pa	6×107
Density of Stainless steel/(kg·m^{-3})	7800
Poisson's ratio of Stainless steel	0.3
Shear modulus of Stainless steel/Pa	7×1010
Wheat flour-wheat flour restitution coefficient	0.2
Wheat flour-wheat flour static friction coefficient	0.65
Wheat flour-wheat flour rolling friction coefficient	0.23
Wheat flour-stainless steel restitution coefficient	0.2
Wheat flour-stainless steel static friction coefficient	0.72
Wheat flour-stainless steel rolling friction coefficient	0.25
JKR	0.145

Simulation process and post-processing

The isometric screw is a conventional screw structure, so the simulation process is illustrated by taking the isometric screw structure as an example. Then pitch value of isometric screw structure is 100 mm. Particle simulation adopts soft ball model, and particle generation method is Dynamic (*Wang et al., 2019; Wen et al., 2020; Luo et al., 2018*). The top of the powder in the hopper is in a horizontal state, and the distance from the center line of the barrel is 400 mm. The screw speed was set as 80 r/min, the simulation step size was set as 0.05s, and the simulation time was set as 10 s.

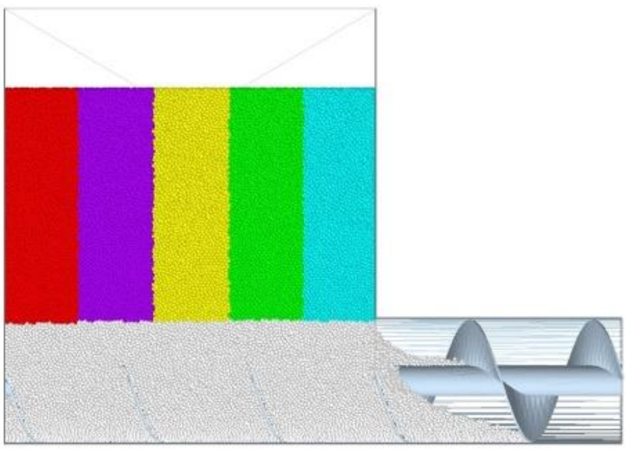


Fig. 5 - Setting of different color ribbons of wheat flour in different areas in the barrel

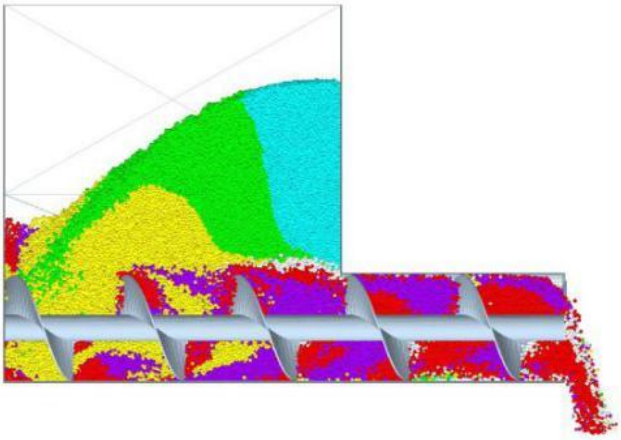


Fig. 6 - Isometric screw feeding state of wheat flour

After the end of the simulation, the feeding uniformity of the screw feeding section was analyzed by the method of references (*Fernandez et al., 2011; Gan et al., 2016; Li et al., 2019*). Manual Selections tool in post-processing is used to establish ribbon areas, and wheat flour was colored before conveying, as shown in Fig. 5. The simulation time was set at 10 s.

As shown in Fig. 6, there is little red and purple in the hopper, and the powder forms obvious funnel-shape. White powder in the screw cylinder has been completely conveyed; the yellow powder in the hopper has been entered the feeding section. Isometric screw structure of the dead zone phenomenon can be clearly observed.

Real experiment of wheat flour screw feeder

In order to verify the feasibility of the design method of variable pitch screw structure, a wheat flour screw feeding experimental platform was built. In the experiment, the feeding uniformity of wheat flour, the flow rate and precision of the screw feed were mainly considered, and the design of the variable pitch screw was evaluated based on the experimental results.

Experimental materials and equipment

Raw materials: wheat flour, Zhengzhou Haijia Food Co., Ltd., water content 13.5%, ash 0.51%, loose density 0.52 t/m^3.

Acrylic cylinder: In order to facilitate the observation of the feeding performance of the screw feeder, the screw feeder cylinder is made of transparent acrylic plate, which is made by Shanghai Baoyou Technology Products Co., Ltd. The size of the acrylic cylinder is designed according to the size of the screw feeder produced by Henan Jingu Industrial Co., Ltd.

Fig. 7 - Screw feeding experimental platform

Variable pitch screw: the three kinds of experimental screw was processed by Henan Jingu Industrial Co., Ltd.. One is the conventional equal-diameter and equal-pitch screw structure, the second is the existing design of equal diameter variable pitch screw structure, and the third is the equal-diameter and equal-distance variable pitch screw structure optimized in this paper. The material is 304 stainless steel.

RS485 plane weighing sensor: Hengyuan Sensor Technology Co., Ltd.，weighing range 0-50 kg, sampling frequency 10Hz-30Hz, measurement error ±0.003 kg.

The acrylic cylinder, screw, motor and other devices are assembled, the installed wheat flour screw feeding equipment is fixed on the table top and placed horizontally, and the experiment platform is set up as shown in Fig. 7.

Wheat flour screw feeding experiment procedures

1) In screw feeding, more wheat flour is needed. Prepare 100 kg of wheat flour before the experiment.

2) Three different speeds were used in the experiment. Before pouring wheat flour into the hopper, the laser velocimetry was used to measure the frequency of the frequency converter corresponding to three different speeds.

3) Adjust the frequency of the frequency converter to meet the speed requirements, pour the wheat flour into the hopper and let the screw feeder operate. After the wheat flour is completely filled into the packing barrel, scrape the top of the wheat flour in the hopper, as shown in Fig. 8.

4) At this time, the camera is fixed and the feeding state is photographed every 5 seconds. When the powder in the hopper reaches the screw blade, the operation is stopped, and the time is about 20 seconds.

5) When the powder in the hopper is basically delivered, the sensor and the feeding device are suspended, and the quality-time data are derived for processing and analysis. The data are measured five times at each speed.

Fig. 8 - Wheat flour state before feeding

RESULTS AND DISCUSSIONS

Simulation results and discussion

Feed flow rate

The feed flow rate is an important index for evaluating the performance of the screw feeder. After the end of the simulation, the fast-filling period of the material is removed, and the feed flow rate is collected during the feed stable time period. The post-processing flow sensor is used to set the position as the discharge port at the end of the barrel to detect the feed flow in the stable period of time in real time (*Dai and Grace, 2008; Evstratov et al., 2015; Jia et al., 2017; Moysey and Thompson, 2015; Nachenius et al., 2015; Orefice and Khinast et al., 2017; Pezo et al., 2018; Rozbroj et al., 2015; Ruiz-Carcel et al., 2018*). The results are shown in Fig. 9.

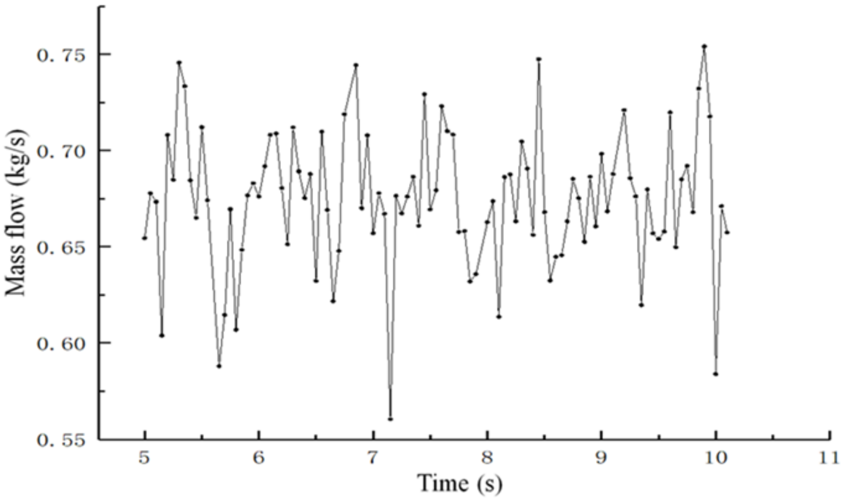
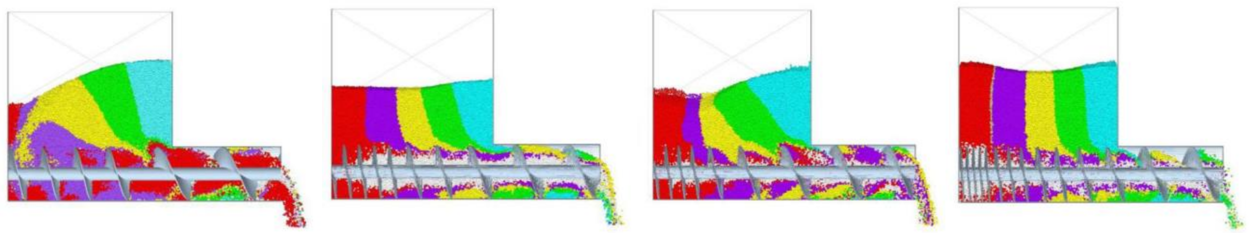


Fig. 9 - The mass flow curve of wheat flour at the outlet of the isometric screw feeder

It can be seen from Fig. 9 that the material flow presents a wave shape in a period of time. This is mainly due to the influence of the termination end face of the screw blade in the feeding of unit screw pitch. When the screw blade rotates to different positions, the blade and the feed cylinder form different storage spaces. In the time of a screw rotation, the unit turn angle presents different feeding amount. It can be seen from the Fig. 9 that the average flow of isometric screw feeding is 0.67 kg/s, and the flow fluctuates within the range of 0.56 kg/s-0.75 kg/s. The flow fluctuates greatly within the range of 11.94%-16.42%, and the precision of screw feeding is small.

Analysis of feeding uniformity of four kinds of screw feeding segments

As shown in Fig. 10, the materials in the hoppers in Fig. 10a and Fig. 10c have formed an obvious inclined funnel shape at this time, showing an obvious large dead zone phenomenon. The blanking of b and d is relatively uniform. The simulation results of the four screw types are shown in Table 3.



a. Single dead zone b. Double dead zones c. Three dead zones d. Four dead zones

Fig. 10 - State diagram of screw feeder with different number of dead zones (t=10 s)

Table 3

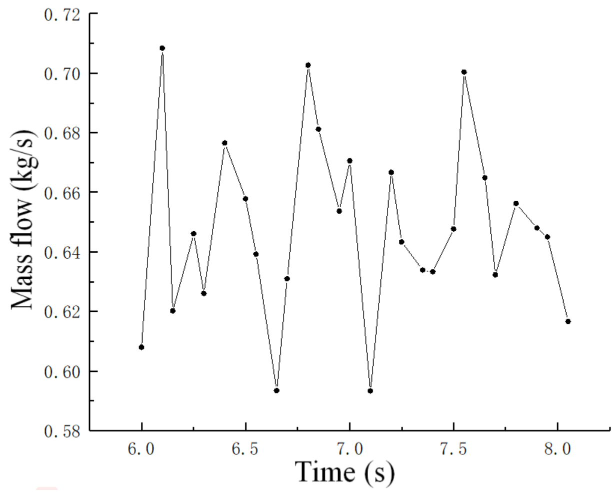
Simulation results of four screws at 10 s

The number of dead zones	Analysis of simulation result
1	The red and purple ribbons have basically completely entered the cylinder, and the area above the first turn of the pitch forms a blanking state, and the obvious blanking dead zone is formed above the other pitches except the first turn of the pitch in the feeding section. At this time, the yellow, green and cyan ribbons all have a tendency to move towards the first screw pitch. (Fig. 10a)
2	The five ribbons in the hopper are basically in a vertical state, and the top edge surface of the five ribbons in the hopper is relatively horizontal, indicating that the feeding is more uniform. (Fig. 10b)
3	The pitch value of the first turn of the structure in Fig. c is small, and the width of the purple and red ribbons is thinner than that of other color ribbons, indicating that there is more blanking here. The top edges of the red, purple and yellow ribbons are horizontal, and the dead zone is mainly in the green and green areas. Compared with Fig. a, the distribution of the dead zone is slightly reduced. (Fig. 10c)
4	Each ribbon in the hopper is basically vertical, and the edges of the five ribbons form an obvious symmetrical concave shape. A large number of white materials are left in the cylinder. There are more white materials in the first pitch value, and the dead zone is mainly distributed at both ends of the feeding section. (Fig. 10d)

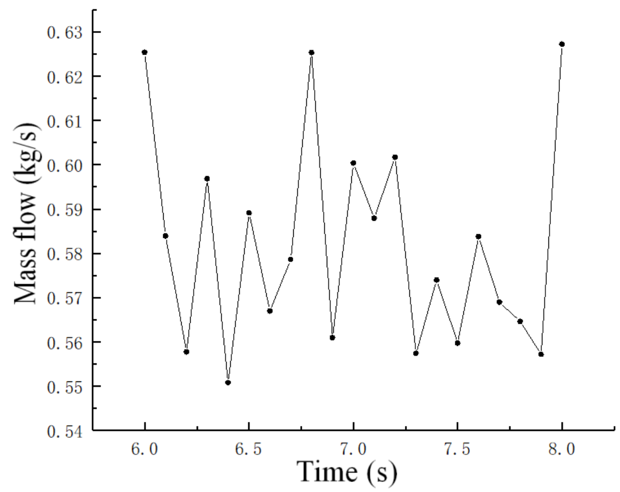
Screw feed flow analysis

After the end of the simulation, the post-processing flow sensor is used to detect the feed flow and collect the mass flow of 6 s-8 s to the discharge port of the cylinder during the stable feeding period, the results being shown in Fig. 11.

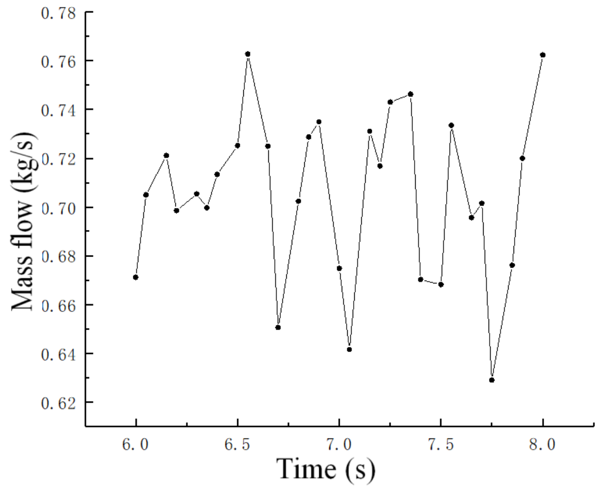
As can be seen from Fig. 11, the average feed flow distribution of each screw is greatly different, for screw a and screw c, the flow size and fluctuation are basically the same. Considering the four dead zones, the feed flow of d screw is relatively reduced, while the feed flow of b screw with more uniform feeding is significantly smaller.



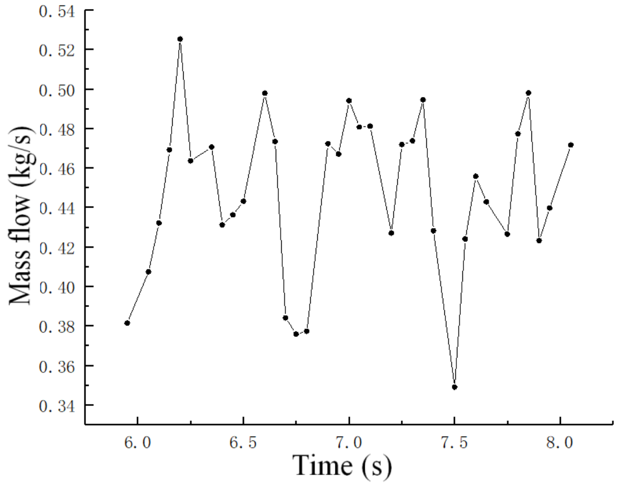
a. Single dead zone



b. Double dead zones



c. Three dead zones



d. Four dead zones

Fig. 11 - Mass flow rate of screw feeder with different number of dead zones (t=6…8 s)

Table 4

Analysis of flow stability of screw feeders with different numbers of dead zones

screw	Average feed flow (kg/s)	Flow fluctuation range (kg/s)	Percentage flow fluctuation (%)
a. Single dead zone	0.648	0.593kg/s-0.708kg/s	±9.26
b. Double dead zones	0.593	0.558kg/s-0.627kg/s	±5.91
c. Three dead zone	0.705	0.629kg/s-0.763kg/s	±8.23
d. Four dead zone	0.447	0.349kg/s-0.525kg/s	±17.45

Optimal design of screw feeder

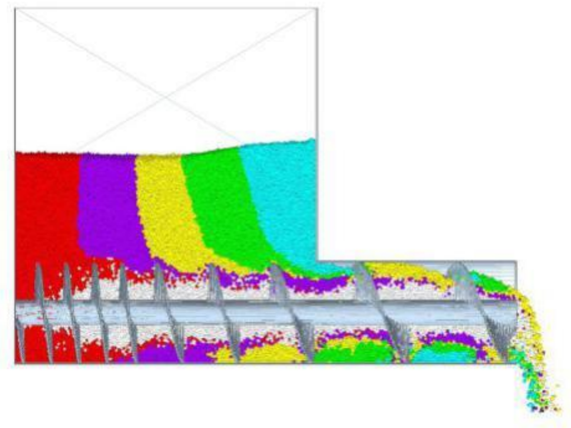
Based on the simulation comparison and analysis of the above four screws, the optimal screw structure was selected, according to the simulation results of the feeding uniformity, the blanking conditions of b and d screw structures were relatively uniform, in which the blanking end face of b screw basically presented a vertical state, while the blanking end face of d screw presented a slight concave type. It can be seen from the mass flow that the flow fluctuation of the b screw is smaller than that of the d-screw, indicating that it has a higher feeding accuracy. Therefore, the structure design of the screw feeder adopts b screw structure (considering two dead zones). Although the average feeding flow rate of a and c screw is large, the fluctuation range of its flow value is large, which affects the weighing speed and accuracy when weighing and quantifying, especially in the fine feeding process.

Contrast and analysis with existing design

According to the relevant reference (Du and Zhao, 2014), the screw pitch design of the feeding section of the screw used to convey wheat flour is generally 0.3D, 0.5D, 0.7D and 1D (D is the diameter of screw blade). The following is a simulation comparison and analysis based on the optimal designed screw structure and the design structure in the reference. For the convenience of comparison and analysis, the screw design in the reference also adopts the same outer diameter, and the same speed. It can be concluded that the screw pitch values of the feeding section designed in the reference are 30 mm, 50 mm, 70 mm and 100 mm, and the screw pitch value of the conveying section is 100 mm.

Comparison of blanking uniformity

As can be seen in Fig. 12 a, the ends of the five color ribbons in the hopper are basically in a horizontal state, and the powder at the outlet of the screw feed are in a mixed state of five colors. As can be seen in Fig. 12 b, the phenomenon of dead zone of materials is more obvious. The red and purple ribbon in the hopper have basically all entered the cylinder, and the Yellow-green-cyan ribbon have formed obvious slip surfaces, all of which have a tendency to slide towards the pitch of the first turn. Compared with Fig. 12 b, the feeding in Fig. 12 a is obviously more uniform.

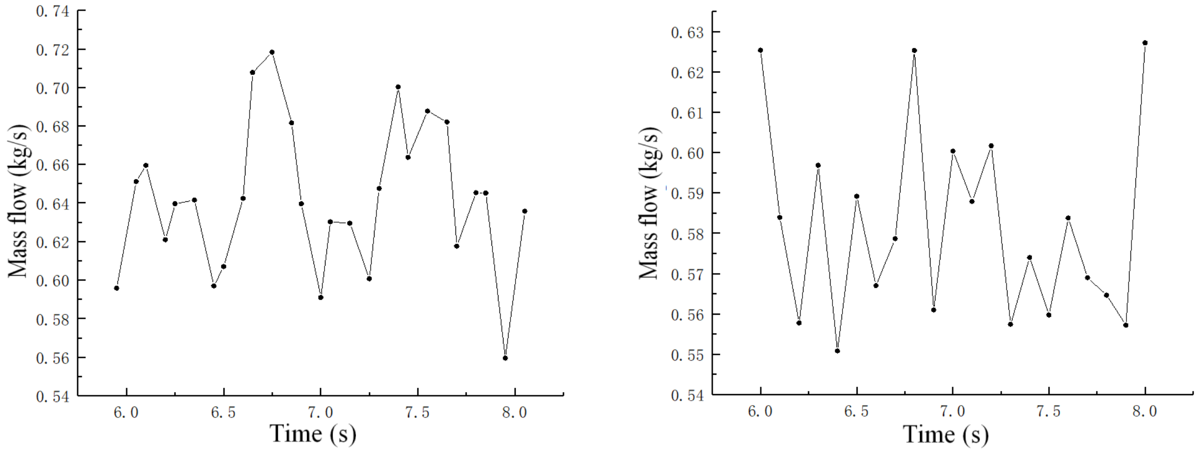


a. Double dead zones *b. Reference design*

Fig. 12 - Comparison of the feeding status of the two dead zones and the reference design screw feeder (t=10 s)

Comparison of feeding flow comparison

As can be seen from Fig. 13, the feed flow distribution of the two helical structures is greatly different, and the feed flow of the two dead zone helical structures is obviously smaller than that of the design in the reference. According to the calculation and analysis of the derived image data, it can be concluded that the average feed flow of the screw with two dead zone is 0.593 kg/s, and the flow fluctuation range is 0.558 - 0.627 kg/s, and the fluctuation percentage is within ±5.91%. The average feed flow of the screw designed in the reference is 0.642 kg/s, the flow fluctuation range is 0.559 - 0.718 kg/s, and the fluctuation percentage is within ±11.83%. According to the experimental data, the flow fluctuation of the screw with more uniform feeding (two dead zones) is relatively small.



a. Double dead zones *b. Reference design*

Fig. 13 - Comparison of mass flow between two dead zones and the reference design screw feeders (t=6…8 s)

Results and discussion of real experiments

Comparative analysis of feeding uniformity

As can be seen from Fig. 14, the material states of the simulation experiment and the real experiment are very similar at 10 seconds, indicating that the simulation experiment is relatively accurate. The surface of the material is relatively flat, indicating that the screw design is reasonable.

a. Simulation state b. Experiment status

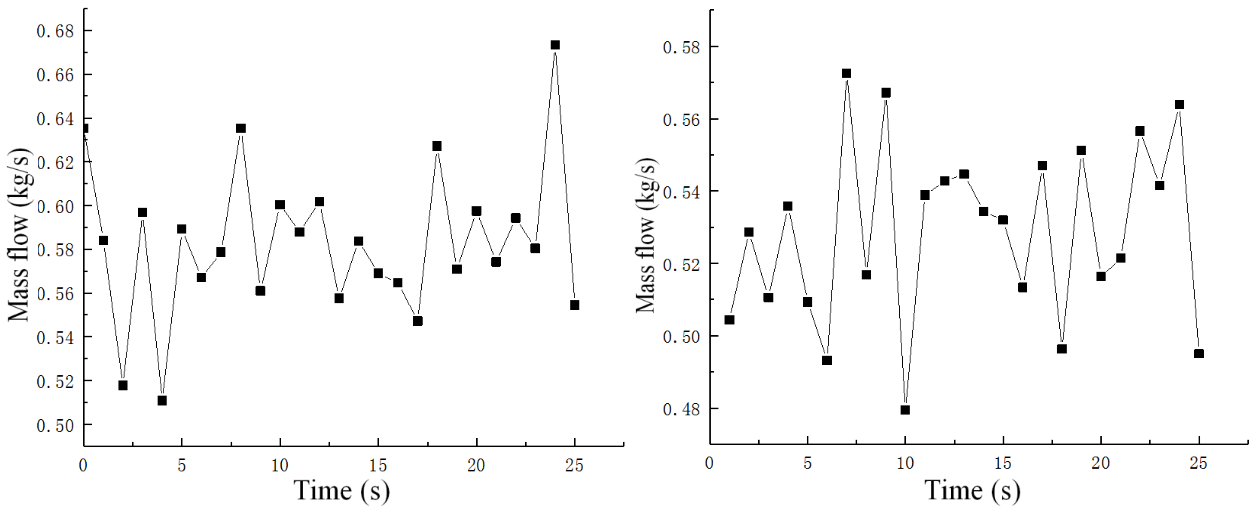
Fig. 14 - Comparison of simulation experiment and real experiment of two dead zone screw feeders (t=10 s)

Comparative analysis of the mass flow

In view of the screw feeding flow of wheat flour, the weighing sensor was used to detect the mass flow rate in real time, and the mass-time curve was derived to acquire the average mass flow rate for evaluation. The real-time detection data were processed (Fig. 15), and the stability and feeding accuracy of the screw structure were analyzed according to the quality-time curve after processing.

It can be seen from Fig. 15 that the experimental results are similar to the simulation results. According to the experimental data, when r=80r/min, the average mass flow rate of wheat flour conveyed by conventional equidistance screw is 0.573 kg/s, and the flow fluctuation range is 0.502 kg/s-0.673 kg/s, and the fluctuation percentage is within ±17.5%. The average feed flow of wheat flour conveyed by the variable pitch screw designed in this paper is 0.535 kg/s, and the flow fluctuation range is between 0.493 kg/s-0.572 kg/s, and the fluctuation percentage is within ±7.85%. Then, the flow fluctuation of the screw designed in this paper is relatively small when the feeding is more uniform.

It can be seen from the comparison of experimental results that the screw structure designed and optimized for this paper has significantly smaller flow fluctuations, stable feeding and higher feeding accuracy.



a. Conventional equidistant *b. Design in this paper*

Fig. 15 - The mass flow curve of wheat flour at the speed of 80r/min for the isometric and the screw feeder designed in this paper

CONCLUSIONS

1) In view of the problem that the equal-diameter variable pitch screw of wheat flour conveying is mainly designed by experience and there is a lack of systematic design method, in this paper, a method of analysis and design considering the symmetry of the number of different dead zones in the feeding section is presented, and four kinds of equal-diameter variable-pitch screw structures are designed. Solid works was used to build the three-dimensional model. EDEM software was imported to analyze the stability and feed flow of wheat flour under screw feeding. Compared with the isometric screw structure and the variable-pitch screw structure designed by the existing experience, the screw structure designed in this paper has the advantages of uniform feeding and small fluctuation of mass flow.

2) In order to further verify the rationality of the variable pitch screw structure design, the screw is processed according to the optimized parameters, and the screw feeding device of the transparent barrel is built using acrylic to observe the stability of the feeding section of the wheat flour. The mass flow rate of wheat flour was measured by plane weighing sensor. When r=80 r/min, the average mass flow rate of wheat flour conveyed by conventional equidistance screw is 0.573 kg/s, and the flow fluctuation range is 0.502-0.673 kg/s, and the fluctuation percentage is within ±17.5%. The average feed flow of wheat flour conveyed by the variable pitch screw designed in this paper is 0.535 kg/s, and the flow fluctuation range is between 0.493-0.572 kg/s, while the fluctuation percentage is within ±7.85%. Simulation and experiment results show that the flow fluctuation of the screw designed in this paper is relatively small, and the feeding is more uniform, which can improve the precision of screw quantitative feeding of wheat flour.

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