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Design of Twin Screw Feather Extruder and Study of Screw Parameters

Haoze Li[1], Ping Jiang[1], Keying Li[1], Huawei Liu[1], Ping Zhang[1], Guohai Zhang[1*]

[1]School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo, 255000, China.

ABSTRACT

Poultry feathers are rich in amino acids and keratin resources, which is a kind of protein feed raw materials with high nutritional value. A twin-screw extruder was designed to deal with the environmental damage caused by the shortage of rapidly developing protein feed and the large amount of feather waste in China's livestock breeding industry. The bulking machine can break the disulfide bond and hydrogen bond in feather keratin to form crude protein which can be absorbed by livestock. A kind of high-protein feed feather powder was developed while protecting the environment. The combination mode and rotation direction between two screws are discussed, the relationship between the key basic parameters of the twin screw is derived by combining the motion principle of the twin screw and the relative geometric position. It provides theoretical basis for determining screw parameters and working condition parameters in the following experimental research.

Keywords: Twin screw extruder; Puffed feather powder; Screw combination; Twin screw structure

***Correspondence to Author:**
Guohai Zhang
School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo, 255000, China.

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Introduction

With the rapid development of poultry and livestock industry in China, the demand for protein feed is increasing. As a necessity in the breeding process, feed has high price cost and unstable quality, which has a great impact on the feed conversion rate. It is an urgent problem to develop and produce a new high protein feed with low cost and good quality [1]. The annual production of chicken feathers in China is high, but most of the chicken feather waste is burned or buried, causing damage to the air and the environment; According to the investigation and analysis, poultry feathers are rich in amino acids and more than 80% protein, and feather processing as livestock feed is one of the effective treatment methods for waste feathers recycling [2-3]. There is enzymatic hydrolysis, hydrolysis, microbiological and expansion methods for the treatment of poultry feather feed [4]. These methods are all chemical methods, which are easy to cause pollution during the treatment process, cause great damage to the environment, and the production process is complicated. As a physical method, puffing method has less damage to the environment than chemical treatment method, and has important research significance in the preparation of feather-based animal protein feed [5].

The puffing treatment of feather can not only effectively protect the environment, make the feather waste produced by poultry breeding industry to be recycled, but also provide abundant and high-quality puffing feather powder for protein feed. Chen Zhimin et al. [6] selected 64 piglets of similar age and average weight in the two groups of experiments designed. One group was fed with corn and soybean meal and the other group was the experimental group. On the basis of the control group, 3 % puffed feather meal was added instead of 6% soybean meal, and the rest was fed with corn. The effects of feeding rate, weight gain ratio and growth status of piglets were analyzed, and the results showed that there was no significant effect in the experimental group. Therefore, the expanded feather powder can alleviate the shortage of protein feed resources in China to a certain extent. In this paper, the feather composition and swelling technology are analyzed, and the structure and design theory of the twin screw feather extruder are preliminarily discussed.

1. Feather composition and puffing process

1.1 The composition of feathers

Feathers are keratinized products derived from poultry epidermal cells. Covering the body surface not only has the functions of cold prevention, temperature regulation and body protection, but also is a tool for some birds to fly. Feathers have a certain rigidity in structure. Because they are rich in keratins, there are generally more than a dozen amino acids, including cysteine, arginine, lysine and methionine [7]. Rich in a variety of amino acids and proteins, the disulfide bond formed by cysteine crosslinking in the peptide chain on its spatial structure makes the feather tough and strong [8], disulfide bond is a kind of stable covalent bond, which plays the role of stabilizing the spatial structure of peptide chain in protein molecules. The greater the number of disulfide bonds, the greater the stability of the protein molecule against external factors, the common pepsin and trypsin can't be digested directly, so feathers are difficult to be degraded and utilized, resulting in a large amount of waste of resources.

1.2 Extrusion puffing technology

Extrusion puffing technology is one of the most widely used materials processing technologies in the food processing industry in recent years. With the development of the feed industry, extrusion puffing technology has gradually been applied to the feed preparation industry due to its advantages such as better final product quality, less environmental pollution and relatively simple production process [9]. Li Jianing et al. [10] respectively summarized the influence of extruded technology on the characteristics of feed raw materials such as corn, bran, soybean and feather, etc. After extruded, the feed quality is better and it is conducive to the protein absorption of livestock. Extruded technology has a broad application prospect and high research value in the future feed production industry.

The twin-screw extruder performs extrusion processing on the feathers. First, the feathers undergo a high temperature and high-pressure process in the cavity of the extruder. At the same time, the feathers interact with the screw and sleeve to generate high shear forces. At this time, the feathers in the machine are molten state. The screw pushes the material axially to the die hole. At the moment of extrusion, due to the sudden decrease of pressure and temperature, the disulfide bonds and hydrogen bonds in feather keratin are broken when they reach a high temperature of 180℃ and a pressure of 1.5 MPa, destroying the firm feather keratin. The space structure of the feather keratin becomes smaller protein subunits or polypeptide chains arranged linearly. The keratin in feathers is puffed to become a crude protein that can be digested and absorbed by livestock, the puffing things are chopped to form feather meal to replace the protein feed components such as soybean meal and imported fish meal in the feed for livestock and poultry. He Wushun et al.[11] determined the digestibility of various amino acids, and found that the digestibility of amino acids reached the level of high-quality soybean meal, which was similar to the level of imported fish meal. Feather powder formed by extruder at high temperature is not only sterilized and matured, but also has good palatability and can be easily absorbed by poultry and livestock. It is a kind of high-quality protein feed.

2. Machine structure and working principle

2.1 Structure of the machine

According to the material characteristics of feather and combined with feather powder puffing process, a twin-screw extruder for puffing feather is designed. The whole machine is mainly composed of a frame, feeding hopper, spiral conveyor, driving system, resistance heater, cooling device, extrusion puffing device and shredder. The structure of the whole machine is shown in Figure 1, the feeding device is mainly composed of the feeding hopper and the screw conveyor, which facilitates the compaction of the feeding feathers in the hopper and the uniform axial transmission to the swelling host to improve the feeding efficiency. The puffing unit is composed of two parallel single screw, sleeve, mold hole and temperature regulating system, which is the key device of the whole machine and the core component of feather puffing. There are two sources of heat in the extruding process of the twin-screw. One is the conduction heat provided by the external heater, and the other is the shearing action between the feather and the screw and the barrel in the expansion chamber, which converts the mechanical energy of the motor into heat energy. The heating device in the figure is a kind of resistance heater with a temperature sensor for real-time temperature monitoring, to meet the requirements of different water content of feathers on the heating temperature. The signal transmission through the temperature sensor is convenient to regulate the specific parameters of the implementation device in the whole machine structure. The cooling device adopts mild oil cooling to prevent the gelatinization of feather material caused by too high temperature in the mold hole and increase the expansion rate during the mold hole. The heating and cooling device forms the temperature regulating system of the expanding host machine, which is more conducive to the production of high-quality feather meal.

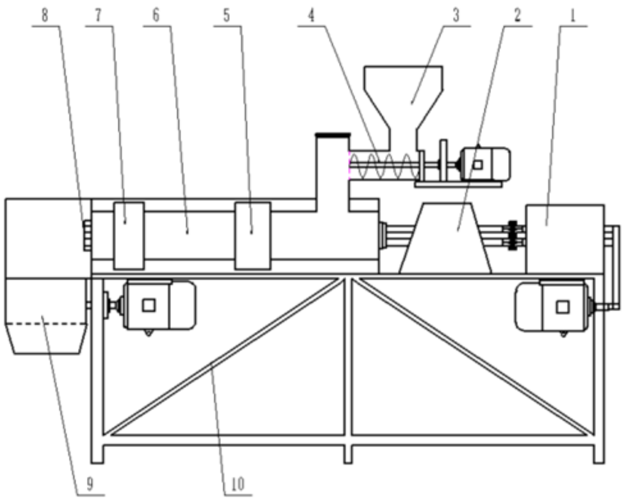

Figure 1. Structure of twin-screw feather extruder

1. Reducer 2. Transmission box 3. Feeding hopper 4. Spiral conveyor 5. Heating device 6. Puffing main machine 7. Cooling device 8. Rack 9. Shredding device 10. The machine frames

2.2 Working Principle

When the twin-screw feather extruder is working, the temperature adjustment system is turned on in advance, and the feathers enter the screw conveyor from the hopper, and the screw conveyor is driven by the motor to evenly transport the feathers to the extruder for extrusion. The feathers are in a molten state under the action of high temperature, high pressure and high shearing force in the twin-screw extruder. They are pushed in the axial direction of the screw to cool and expand at the moment of the die hole, forming loose feathers, and then fall into the cut. In the shredder, the shredder grinds it into powder, and after it is completely cooled and dried, it forms a high-quality protein feed puffed feather meal.

3. Key parameter design theory of twin screw

3.1 The meshing mode and rotation direction of the twin screw

Twin screw is composed of two parallel single screw, which can be divided into two forms of full meshing and non-meshing [12]. The two screw rods meshing have the same depth of the screw groove, and because the screw edge shape and the screw groove shape are closely matched, a good seal is formed between them. The building pressure ability is strong, but the mixing ability of the material is weak. However, there is a gap between the two non-meshing screws, which has a strong material mixing ability. Because there is a gap between the screw groove and the screw edge, its building pressure ability is weak [13].

In the twin-screw direction, it is divided into the same direction rotation and the different direction rotation. If two screws are rotating in the same direction, the thread direction must have the same rotation, that is, the thread is right-handed or left-handed; If two screw threads are rotating in opposite directions, their threads must be in opposite directions, that is, one is left-handed and the other is right-handed. As shown in Figure 2, there are two ways of rotation, one in the same direction and the other in the opposite direction. The linear velocity direction of the two screw in the meshing area is the most important factor to distinguish the two rotation modes. The linear velocity direction of the two screw in the meshing area is opposite to the meshing direction. Therefore, the combined double-screw thread element has a good mixing effect in the meshing area, but it cannot form a closed chamber between the two screws when working. The material is transported along the ∞ type spiral axial direction between two screw and barrel, the continuous thread channel makes the material from one screw to another screw slot. When the pressure of one screw increases, the pressure of the other screw will decrease relatively. The twin screw that rotates in a different direction basically constitutes a closed screw slot, and the upper part of the meshing part establishes a high pressure which has a strong squeezing effect on the material [14].

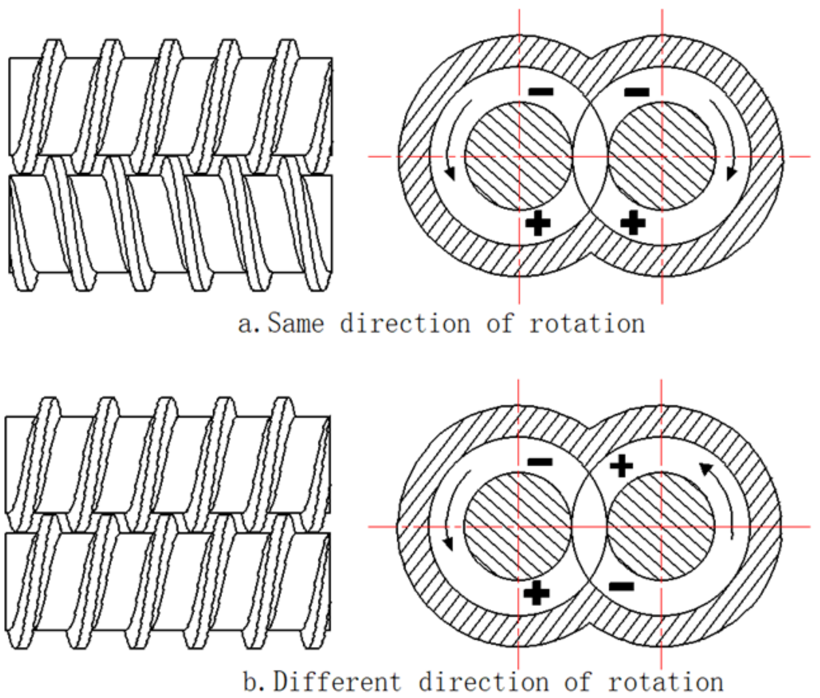

Figure 2. Twin-screw combination and rotation mode and pressure distribution

3.2 Movement principle of twin screw with different rotation directions meshing

Figure 3 is the analysis of the motion principle of the twin screw rotating in meshing opposite direction. It is assumed that disc 1 is fixed and disc 2 with radius AM_2 rolls around the base circle with radius AM_1. Each point on disk 2's circumference, depending on its distance from M2, will be able to depict an extended or shortened ellipse. If the upper arc P_1P_2 of disc 2 is the top of the thread, the two center points P_3 and P_4 on this arc can depict the family of cycloid lines cut off from disc 1. The shape of the cut surface area is the same as the cross-cut area of the spiral groove perpendicular to the rotary axis. If a thin disk with surface area is cut off in this way and transferred forward or backward along the axis direction, a positive or spiral will be generated, whose helical surface is formed by a series of cross-sectional areas cut out by the cycloid family. Each point on the side of the helix will be swept by another screw, similar to a pair of meshing gears rolling against each other. The relative velocity *v* of each swept point depends on the distance between these points and the rotary axis, which can be expressed as:

$$-2\pi\, n(R_i - R_o) \le v \le +2\pi\, n(R_i - R_o)$$

In the formula, R_i is the inner radius, mm; R_o is the screw radius, mm; n is the screw speed, r/min.

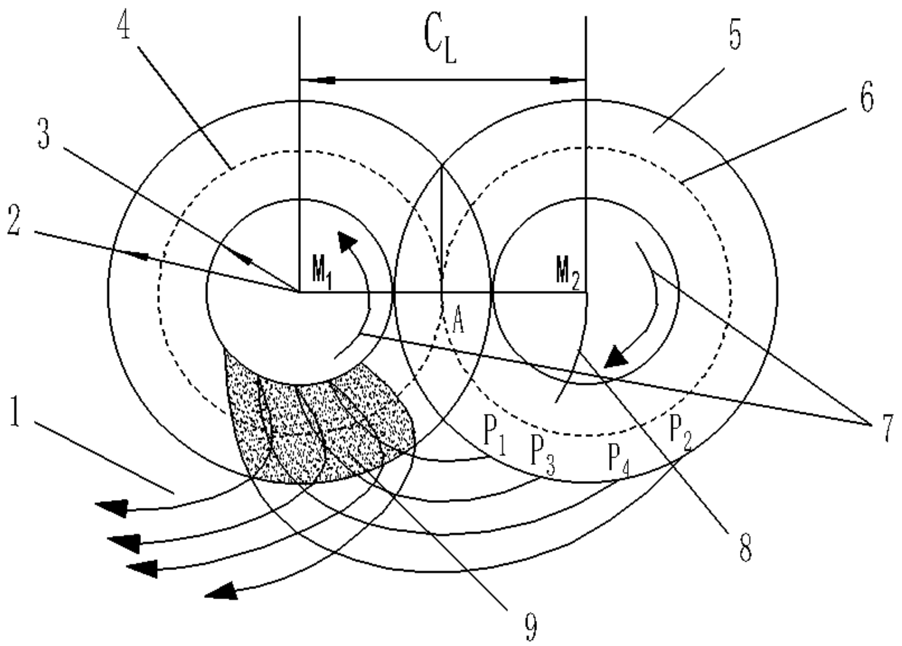

Figure 3. Principle of twin-screw movement in different rotation directions

1. Cycloid family 2. Outer radius R 3. Inner radius R_i 4. Disk 1

5. Disc 2. 6. A circular path for scrolling 7. Direction of rotation

8. Movement of M_2 when disc 2 rolls around fixed point 1. 9. Cut surface

3.3 Relative position and main geometric dimensions of twin screw

Screw as a key part of twin-screw feather extruder, the parameters of screw extruder affect the yield and quality of feather extruder. Based on the above analysis, Figure 4 shows the relative positions and main sizes of the two screws in the meshing twin screw extruder, so the geometric relations of the twin screw with different rotation directions of meshing can be discussed. If the center distance of the two screws is C_L and the outside diameter of the two screws is the same as D, then when C_L is less than D, the two screws are engaged. Center distance and screw diameter determine the meshing Angle α_i and meshing height I_h. The relationship between engagement Angle α_i, screw diameter D and center distance C_L can be expressed as:

$$\cos(\frac{1}{2}\alpha_1) = \frac{C_L}{D}$$

The meshing height can be expressed as:

$$I_h = \frac{1}{2} D \bullet \sin(\frac{1}{2}\alpha_i)$$

The relationship between center distance, outside diameter of screw and root diameter of screw is as follows: $D_r = 2C_L - D$

Then the depth of the screw groove H can be expressed as: $\frac{H}{D} = 1 - \frac{C_L}{D}$

The depth of the screw slot is an important parameter, and the deeper of the screw slot can obtain a large theoretical extrusion amount for feather material. This lengthens the length of time the feather stays in the slot, which is particularly beneficial for the unpressurized screw section. It can be clearly seen from the above formula that as the center distance increases, the depth of the spiral shell decreases and the cross-sectional area of the spiral shell decreases. Increasing the center distance will reduce the screw transport capacity. In order to obtain high conveying capacity, the center distance must be small under the condition that the outside diameter of screw is unchanged.

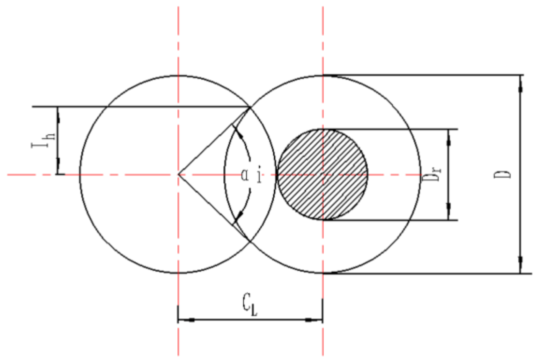

Figure 4. Relative position and main dimensions of twin screw

3.4 Screw length-diameter ratio and center distance

The ratio of screw length to diameter is an important technical parameter of feather bulking machine, and its size directly affects the efficiency of the machine to complete specific production tasks and functions. The increase of the aspect ratio within a certain range can effectively establish the pressure required by the normal operation of the extruder and increase the heating time of the material, which has a positive effect on changing the structure of keratin in feathers. Screw length-diameter ratio refers to the ratio of screw top thread length to screw diameter, which is expressed by *L/D*, where *L* represents thread length and *D* represents screw diameter. The diameter of the screw affects the performance of feather extruder, such as the extruder volume, the type of material to be processed, the product specification and the use of the extruder. Domestic scholars have conducted in-depth research on the length-diameter ratio of twin-screw extruder for processing other materials, but there are few researches on feather puffing machine. At present, the length-diameter ratio of twin-screw extruders used in industrial production in China is between 21 and 33. Since the laboratory has a larger demand range for the length-diameter ratio, the selection of length-diameter ratio applied in the laboratory is wider [15]. The distance between two screw shafts is called the center distance of the screw and is an important parameter, which is of great importance to the depth of the screw slot, meshing property, conveying mechanism and structural design. The expression is as follows: $C_L = \frac{D_r}{2} + \frac{D}{2}$

In the formula, C_L is the center distance, mm; D_r is the internal diameter of the screw, mm; D is the diameter of the screw, mm;

The center distance determines the outside diameter and root diameter of the screw, thus determines the size of the meshing area and the depth of the screw slot of the two screws, and also determines the size of the drive shaft and gear, thus determining the effective torque of the screw.

3.5 Compression ratio

The geometric compression ratio ε of a twin screw is the ratio between the volume of a screw slot in the feeding section and the volume of a screw slot in the compression section. Generally, the compression ratio should be between 1.4-2.4. The compression ratio should be lower for materials with high viscosity, otherwise the screw and barrel will wear out. The whole screw is divided into three functional segments, as shown in Figure 5, the material conveying section, compression melting section and homogenization section are respectively. The conveying section is an area under the hopper. Its main function is to compress the feather falling from the hopper and ensure the smooth axial conveying of the material, preheat and buffer the feather material and establish the pressure. Therefore, it is required that the screw pitch in this section is large to improve the conveying capacity. The compression section is mainly to rapidly melt feather material at a given temperature. Under the action of high temperature, high pressure and high shear, the protein structure in feather will change. Therefore, the pitch will change from large to small, and the volume of spiral tank will gradually decrease to build pressure in the cavity, so as to enhance the shearing action between feather material, screw and barrel. The main function of the homogenization section is to transport the feather material which has been melted in the compression section to the mold hole of the screw in a fixed quantity and temperature, and to cool the expansion in the instant of the mold hole. This section is generally of equal distance and depth. Changing the pitch in sections is also the method usually adopted by the more popular combined twin screw at present. The compression ratio of the three sections can be selected separately according to the functions.

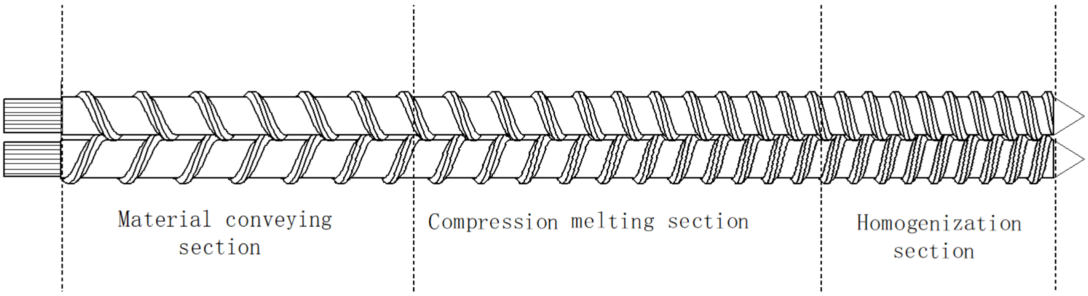

Figure 5. The three functional segments of the twin screw

If the influence of the transition arc is excluded, the compression ratio is calculated according to the following formula:

$$\varepsilon = \frac{\pi(S_1 - m_1 e_1)(D_1 - d_1) - 4F_1 S_1}{\pi(S_2 - m_2 e_2)(D_2 - d_2) - 4F_2 S_2}$$

In the formula, S_1 and S_2 are the pitch of feeding section and compression section respectively; E_1 and E_2 are the number of threads in feeding section and compression section respectively; M_1 and M_2 are the number of threads in feeding section and compression section respectively; F_1 and F_2 are the meshing area of feeding section and compression section respectively.

3.6 Shape of spiral edges and spiral groove section and thickness of spiral edges

The shapes of spiral edges and groove sections of common twin screws that mesh with each other and rotate in different directions are rectangle, trapezoidal and zigzag, as shown in Figure 6:

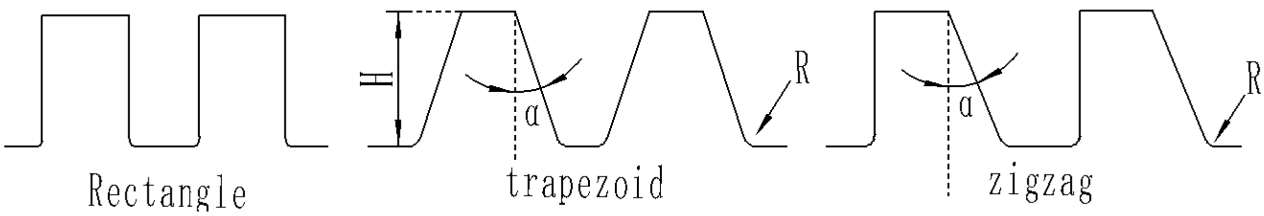

Figure. 6. Shapes of spiral edges and spiral grooves

The rectangular section of the screw groove volume is large and easy to store material; The trailing edge of the spiral edge of the serrated section has A large inclination Angle α (α > 30°) and Larger arc, the mixing and homogenizing effect of the material is better, and its strength is also high, but the volume of the spiral groove is reduced more. The spiral groove of trapezoidal section has the advantages of both of the above two sections, so it is mostly used in practice. The internal inclination Angle of the normal section is α=10°～15°, Arc radius *R*= (0.1～0.15) *H*, where H is the depth of the screw groove. Generally, the value range of screw edge thickness *e* is between (0.08~0.12) *D*, because the thickness of the screw edge is too large, it will affect the volume of the screw slot, make it reduce and increase the power consumption, reduce the production capacity. The relationship between the thickness of the screw edge, pitch, number of threads, diameter of the screw and the center distance of the two screws is expressed as follows:

$$e = \frac{S}{2\pi}\left(\frac{\pi}{m} - 2\sin^{-1}\frac{1}{C_L}\sqrt{\frac{D^2 - {C_L}^2}{S}} + \sin^{-1}\frac{2}{D}\sqrt{\frac{D^2 - {C_L}^2}{3}}\right)$$

In the formula, *e* is the thickness of the spiral edge, mm; *S* is pitch, mm; *m* is the number of threads.

4. Conclusion

In this paper, the feather composition and extrusion technology were studied. On this basis, a twin-screw extruder for feather extruding was designed. The purpose is to produce a high-quality protein feed to alleviate the shortage of protein feed in my country's livestock breeding industry, reduce feed costs and increase feed conversion rate, and to treat discarded feathers to a certain extent to protect the environment and achieve sustainable agricultural development.

A combination of twin-screws with intermeshing and different rotation modes suitable for feather puffing is selected, and the movement principle of the two screws is analyzed, the relative positions of the intermeshing twin-screws are explained, and the relationship between the basic parameters of the screws is derived, which is the twin-screw for subsequent puffing feathers The design and experiment of the feather extruder provide a theoretical basis for determining the working parameters of the feather extruder.

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