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Analysis of Factors Affecting the Molding Efficiency of Straw Pelletization and Optimization of the Pelletization Process

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Abstract: *In this paper, In order to reduce the waste of resources and environmental pollution caused by the burning of straw, in recent years, the country has vigorously promoted the resource utilization of straw. In the process of utilizing straw as feed, traditional pelletizers are limited and cannot address the issues of low nutritional content and significant fluctuations in moisture content of straw. These problems result in low feed molding efficiency, poor quality, and reduced utilization of straw as feed. To address the aforementioned issues, this project proposes a novel device for pelletizing straw. The developed device can effectively enhance the nutritional content of straw feed and control its moisture content. This, in turn, further improves the molding efficiency and quality of straw feed, ultimately increasing the overall utilization rate of straw as feed.*

Keywords: *Straw, feed conversion, nutritional components, moisture content, molding efficiency*

1. Introduction

By 2015, the theoretical amount of straw resources had reached 1.04 billion tons, steadily increasing year by year. With abundant straw resources, a high proportion of which are recyclable, it could potentially become a primary raw material for bio-manufacturing. Therefore, in recent years, the country has vigorously promoted the resource utilization of straw, achieving a comprehensive utilization rate of over 80 [1]. However, China's utilization of straw remains relatively rudimentary, with a low rate of material utilization and a lack of effective utilization methods. For instance, the upper part of maize straw is often used directly as animal feed without processing, limiting the added value of straw products. Furthermore, some resort to directly burning straw, leading to significant resource wastage and environmental pollution.

With the increasing demand for pellet feed due to the popularization of automated livestock farming technology, it provides a feasible solution for the efficient utilization of straw. The utilization rate of straw as feed has been increasing annually, rising from 2.8% in 2000 to 18.8% in 2015, approximately 170 million tons. This indicates the broad prospects of utilizing straw as feed. As a usable biomass energy source, processing straw into pellet feed can effectively alleviate the pressure on feed demand and mitigate environmental pollution caused by straw burning.

2. Method and evaluation

2.1 Raw materials

The cotton stalks mentioned are sourced from Jingmen County, Jingzhou City, Hubei Province, China, and are intended for use in pelletized feed.

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2.2 Additives

In the original straw pellet feed preparation process, an appropriate amount of corn flour is mixed. Corn flour not only increases the nutritional content of the feed product but also further enhances the pellet forming rate of the device.

The nutritional content of the feed made from the mixed ingredients is improved. Compared to traditional straw feed, the feed produced by this device has a more comprehensive nutritional profile, as shown in Table 1 below.

Table 1: The nutritional composition of straw feed pellets at different corn flour ratios.(%)

Corn Flour Ratio	Moisture Content	Crude Protein	NDF	ADF	Ca	P
0%	5.79	6.95	45.43	61.58	0.65	0.11
5%	6.05	7.06	43.69	58.65	0.62	0.13
10%	6.21	7.18	41.19	53.84	0.59	0.14
15%	6.43	7.31	38.89	52.21	0.57	0.14
20%	6.63	7.40	36.94	51.70	0.53	0.15

2.3 Design of Straw Pelletizing Device

The cotton stalks mentioned are sourced from Jingmen County, Jingzhou City, Hubei Province, China, and are intended for use in pelletized feed.

2.3.1 Overall Device Design

The device is divided into four modules: Moisture Control Module, Crushing and Mixing Module, Compression and Cutting Module, and Roller Molding Module, as shown in the overall device diagram (Figure 1) below. The Moisture Control Module detects the moisture content of straw at the inlet, estimates the overall moisture content through multiple data analyses, and controls the moisture content of straw using hot air and steam flow valves. The Crushing and Mixing Module uses high-speed rotating blades to crush materials and achieves internal solid powder mixing through the self-rotation of a V-shaped mixing structure. The Compression and Cutting Module cuts the chunky material by engaging with groove knives, dividing it into uniformly sized small pieces for easy transportation and weighing. The Roller Molding Module controls the particle size by adjusting the coincidence of the through-holes in the two layers of the molding die.

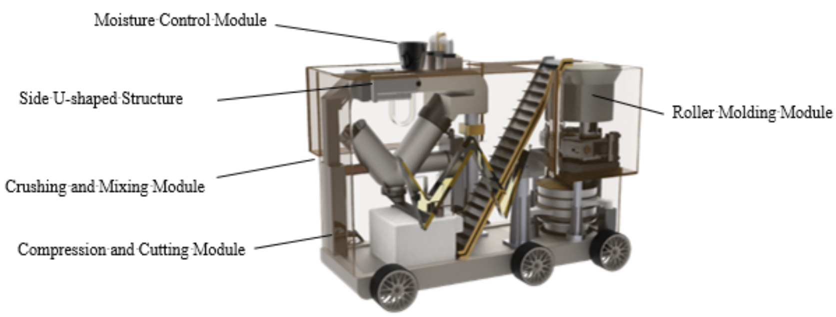

Figure 1: The overall device diagram

2.3.2 Moisture Control Module

The moisture control module comprises an inlet, moisture sensor, motor, reducer, stirring rod, steam flow control valve, and hot air control valve, among other devices. Its specific structure is illustrated in the diagram below (Figure 2).

To address variations in moisture content in different straw types, a device capable of controlling moisture content is designed. At the inlet, a moisture detection sensor is installed to assess the moisture content of the straw entering the device. When the moisture content is detected to be too low, the straw enters the upper part of the side U-shaped structure. Within the upper pipeline, a motor and its reducer drive the rotational motion of the stirring rod. Simultaneously, a steam flow control valve is mounted on the upper pipeline surface. Through analysis of data from the moisture sensor, the device regulates the speed of the atomizer converting water into steam and the flow rate of the valve outlet, thereby controlling the flow of steam added to the upper pipeline. By combining steam intake and the rotation of the stirring rod, thorough and uniform mixing of straw and steam is achieved, humidifying the straw to increase its moisture content to the desired level for processing.

In the event of detecting excessively high moisture content in the straw, the steam flow control valve on the upper surface closes, and the hot air control valve on the lower surface opens. Analyzing data from the moisture sensor, control of the heat pump and blower is employed to regulate the flow rate and temperature of the incoming hot air, facilitating the drying of the straw. This process reduces the moisture content of the straw to the desired level for device processing.

Figure 2: Moisture Control Module

2.3.3 Crushing and Mixing Module

The Crushing and Mixing Module mainly consists of a hammer-type crushing structure, V-type mixing structure, water pipes, sprinkler discs, stirring rods, and a motor, as illustrated in the diagram below (Figure 3).

The hammer-type crushing device is located at the corner of the vertical pipe of the U-shaped structure and the lower pipe. It primarily includes a motor, a rotating shaft, hammers, a cylindrical track, and a conveyor belt. When straw enters the inlet from the vertical pipe, it moves downward along the cylindrical track. At this point, the motor drives the rotation of the shaft, subsequently causing the hammers to rotate around the cylindrical track. The hammers compress and crush the straw feed on the track, turning it into powdered particles. The straw particles then fall from the bottom of the cylindrical track onto the conveyor belt, which transports them forward for a certain distance. Afterward, they drop from the vertical pipe into the V-type mixer for material mixing [2].

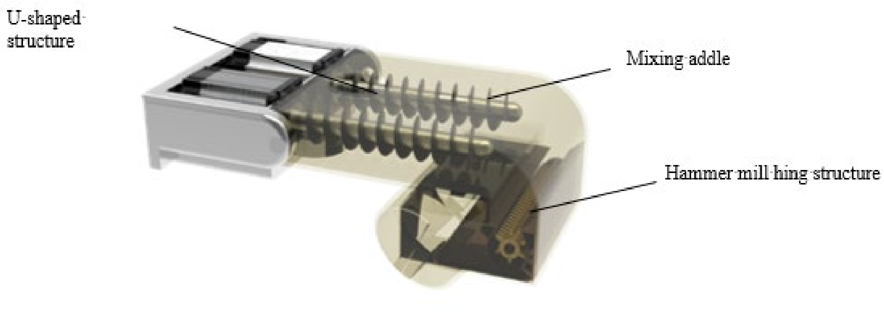

Figure 3: U-shaped structure and its internal device

The V-type mixing device includes a V-shaped main structure, a through-water pipe, a sprinkler disc, a water storage tank, lateral stirring rods, a fixed base, etc., as shown in the diagram below (Figure 4). When powdered straw particles enter the device from the right-side inlet, corn powder is introduced through the left-side inlet. Connected to the fixed base through a rotating shaft, driven by the motor, the V-shaped main body rotates, mixing the internal powders. Additionally, there are lateral stirring rods inside that can be rotated by the shaft to achieve more uniform material mixing.

Considering the support rod on one side of the V-shaped mixing structure for introducing corn powder, this can be achieved through a retractable powder nozzle corresponding to the inlet of the V-type mixer.

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When corn powder needs to be introduced, the powder nozzle contacts the inlet, allowing corn powder to be sprayed into the mixer at a specified rate from the storage tank. When mixing is required, the powder nozzle retracts, and simultaneously, one end of the mixer opens and closes, entering a sealed state.

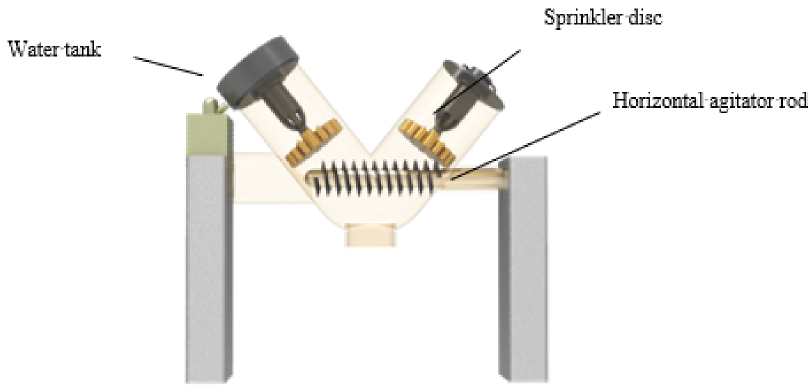

Figure 4: V-type mixing device

2.3.4 Compression Cutting Module

The compress and cut module comprises mainly a hydraulic rod, upper pressing plate, cutting blade, and groove blade. When the mixed feed falls to the bottom of the compress and cut device, the hydraulic rod initiates the downward movement of the upper pressing plate, exerting pressure on the mixed feed at the bottom. Vertically oriented cutting blades are spaced on the bottom surface and correspond to groove blades recessed in the upper pressing plate, as illustrated in the diagram below (Figure 5).

While the upper pressing plate compresses the mixed feed into blocks, the cutting blade and groove blade continuously engage and separate, dividing the compressed block into evenly sized small pieces. This facilitates the subsequent transportation on the conveyor belt and weight measurement by the gravity sensor.

Once the compression and cutting process is complete, the accumulating small pieces are weighed, transported upward through an inclined conveyor belt, and enter the top of the roller compaction device for pelletizing. When a sufficient weight of mixed feed is measured, the conveyor belt stops transporting until the pelletization process concludes.

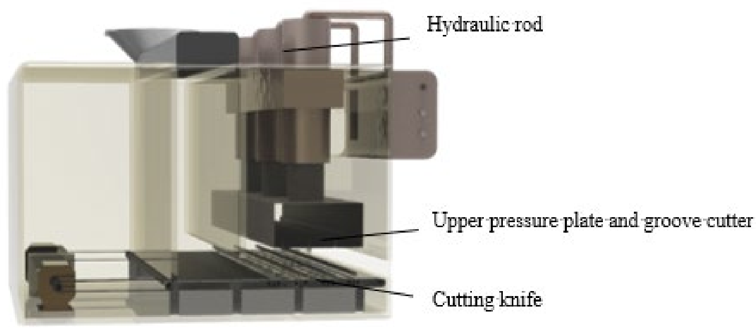

Figure 5: Compression cutting block device

2.3.5 Roller Press Molding Module

The roller compaction module mainly consists of a feeding chamber, molding die, rotary shaft, transmission rod, and pressing rod. The molding die has molding holes arranged along the circumference of the revolving pressing rod, and the upper surface of the molding die forms a stepped structure descending from the center towards the periphery. The molding die is layered, as shown in the diagram set 1 and figure 6 below.

Considering the similar molding of the double-layer molding die, the molding die takes on a circular shape. The inner wall of the intermediate exchange features a meshing structure, allowing control over whether it connects to the central rotary shaft. This control enables the alignment of the molding holes in

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the two layers of the molding die, thereby achieving control over the particle size of the granules in the roller compaction molding section.

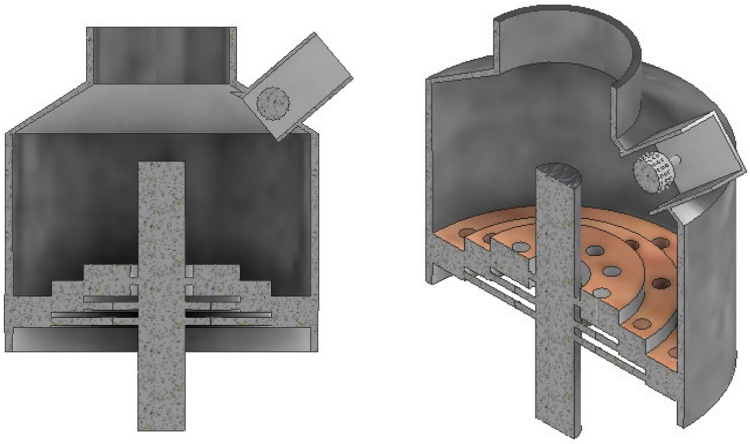

Diagram Set 1 Internal structure of the molding section

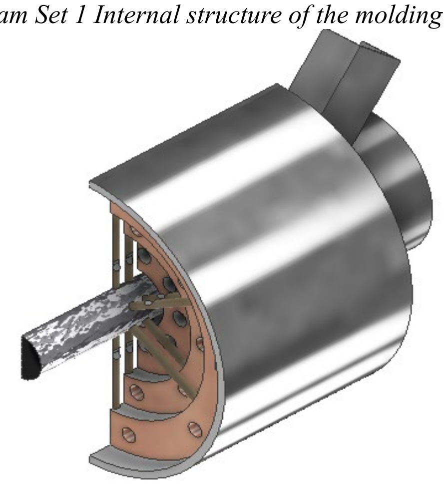

Figure 6: Structure of the Molding Die Components

3. Feasibility Analysis

3.1 Feasibility Analysis of the Material Mixing Module

After comparing the advantages and disadvantages of existing material mixers and considering the material mixing characteristics of this device, the V-type material mixer was selected for this setup. Additionally, considering the characteristics of this device and the drawbacks of V-type material mixers, cleaning structures such as a scattering plate were added internally to facilitate cleaning of the device[3].

3.2 Effect of the Device on Pellet Forming Rate Enhancement

To analyze the feasibility of improving the pelletization rate of straw, pelletization experiments can be conducted. The pelletization rate of pellet feed is taken as the experimental index (y). Before each experiment, the straw pelletizer is emptied, and after running empty for 3 minutes, straw material and corn starch are added for pelletization. All the feed at the final discharge port is collected, and after separately weighing the mass of the formed pellets and the total mass, the pelletization rate is calculated:

$$y = \frac{m}{M} \times 100\% \tag{1}$$

In the equation,y represents the pellet feed pelletization rate, expressed as a percentage (%);m stands for the mass of formed pellet feed, measured in kilograms (kg);M denotes the total mass of material at the discharge outlet, also measured in kilograms (kg).

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The regression mathematical model for the pelletization rate of straw with this device can be obtained through regression analysis using Design Expert software, based on the experimental data calculated from the aforementioned:

$$\begin{aligned} y = 97.65 + 1.09x_1 - 0.75x_2 - 1.14x_3 + 0.38x_1x_2 + 0.30x_1x_3 \\ -0.38x_2x_3 - 1.49x_1^2 - 0.87x_2^2 - 0.61x_3^2 \end{aligned} \tag{2}$$

In the equation, y represents the pelletization rate, expressed as a percentage (%);X_1 stands for the moisture content, measured in percentage (%); X_2 represents the die roller gap, measured in millimeters (mm); X_3 denotes the main shaft speed, measured in revolutions per minute (r/min).

The regression analysis of the equation reveals that the primary influencing factor on the pelletization rate of the device is the moisture content of the straw raw material. However, both the die roller gap and the main shaft speed also impact the product's pelletization rate. To obtain the optimal combination of process parameters, it is necessary to employ multi-objective nonlinear optimization theory to conduct optimization analysis on its regression equation.

$$y = f(x_1, x_2, x_3) \rightarrow max \tag{3}$$

$$\begin{cases} y \geq 0 \\ -1.682 \leq x_1 \leq 1.682 \quad (i = 1,2,3) \end{cases} \tag{4}$$

In the equation, y represents the experimental indicator - pelletization rate, expressed as a percentage (%);X_1 denotes the influencing factor;i represents the number of influencing factors[4].

4. Conclusion

The optimal parameters for pelletizing with this device are: moisture content of 16.62%, die roller gap of 0.28mm, and main shaft speed of 140.74r/min. At this point, the pelletization rate of straw can reach 98.33%, compared to the traditional straw pelletizer's rate of 88%, representing an increase in pelletization rate of approximately 10%.

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