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DESIGN OF BIDIRECTIONAL SCREW EXTRUSION BIOMASS HONEYCOMB BRIQUETTE MACHINE

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Abstract - Biomass densification machines can compress crushed crop straw and other agricultural residues into biomass densified fuels with a specific shape and density under certain external force, temperature, and humidity conditions. Existing biomass densification machines primarily produce solid biomass fuels in the form of rods, blocks, and pellets. In order to improve the moulding efficiency of biomass briquette machines and increase the effective contact area between biomass fuel and oxygen during combustion, a bidirectional screw extrusion biomass honeycomb briquette machine is designed. The briquette machine consists of two main components, the screw extrusion device and the moulding device. The screw extrusion device facilitates continuous material transport via a screw, while the moulding device compresses the crushed biomass material into a honeycomb shape within the moulding sleeve through a crank-slider mechanism. Additionally, since the densification machine compresses the biomass material from two directions, it enhances the production efficiency of biomass densified fuels. The design of this briquette machine is of significance for promoting the widespread use of biomass densified fuels.

Keywords: Screw extrusion; Biomass; Honeycomb briquette; Briquette machine.

1. Introduction

Biomass densification technology refers to the technology of compressing crushed crop straw and other agricultural residues into biomass densified fuels with a specific shape and density under certain external force, temperature, and humidity conditions [1-5]. Biomass densified fuels have some advantages such as easy storage and transportation, high calorific value, and no pollution [6-7].

Francis Inegbediona et al. designed a screw extrusion forming machine, while Xiang Yu et al. developed a biochar extrusion forming machine. Both types of machines are primarily used to produce rod-shaped biomass densified fuels (as shown in Figure 1(a)) [8-9]. Wang Weiwei et al. designed a bionic vertical ring die biomass pellet machine based on a honeycomb structure, and Di Mingli et al. developed the LH-600 biomass pellet forming machine. These two types of machines are designed for producing biomass pellets (as shown in Figure 1(b)) [10-11]. Wu Gaofeng et al. optimized the forming cylinder of a hydraulic piston press forming machine, while Cai Hongzhen et al. designed a vertical plunger press biomass forming machine. Piston press forming machines produce block-shaped biomass densified fuels (as shown in Figure 1(c)) [12-13]. These three types of forming machines produce solid biomass densified fuels, which reduce the effective contact area between the biomass fuel and oxygen, leading to a slower combustion rate and lower calorific value. Additionally, most forming machines adopt a unidirectional feeding mechanism for biomass materials, which decreases the forming efficiency of biomass densified fuels.

(a) Rod-shaped (b) Pellets (c) Block-shaped

Figure 1: Solid biomass densified fuels

To address these issues, a bidirectional screw extrusion biomass honeycomb briquette machine has been proposed [14-16]. The slider of the extrusion moulding part of this machine is uniformly

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distributed with punching pins, which, in combination with the screw extrusion device, compresses the biomass material into a honeycomb shape within the moulding sleeve. This design increases the effective contact area between the biomass fuel and oxygen, thus improving the combustion rate of the biomass densified fuels. Furthermore, since this machine compresses and moulds the biomass material from two directions, it increases the production rate of biomass densified fuels.

2. Performance Comparison of Common Biomass Solidification Forming Equipment

Before the processing of biomass material, the screw extrusion forming machine needs to be heated and preheated, thus increasing the power consumption for producing each ton of biomass fuels in the extrusion forming process. Therefore, this type of equipment has the problem of high energy consumption. In addition, the output of this type of equipment is not high, which cannot meet the needs of actual production. At the same time, the main working component of the screw extrusion forming machine is the screw, and its service life shall not exceed 500 hours at most.

As the piston punch forming machine only extrudes the biomass material in the forming hole, its extrusion energy consumption is about effective energy consumption, so it has the advantage of relatively low energy consumption. However, because it can only realize the extrusion forming of biomass material once a time, it has the problem of low productivity. At the same time, the forming cavity of the piston punch forming machine is easy to wear, and it is generally repaired once every 100h, but some biomass material with less SiO_2 can last for 300h.

Compared with the first two types of forming machines, the die roll forming machine is evenly distributed with many forming holes on the inner or outer surface of the ring die. The roller can extrude the biomass material in multiple forming holes at the same time, so the productivity is greatly improved. However, the traditional die roll forming machine uses the outer curved surface of the ring die and the roller to extrude, therefore, the biomass material at the unopened position of the ring die are also squeezed unnecessarily, which results in additional energy loss and increases the energy consumption of the die roll forming machine.

In summary, the characteristics of various types of biomass solidification forming equipment can be summarized as shown in Table 1 [17-19].

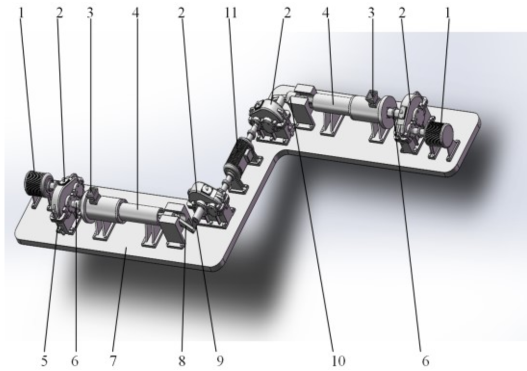
Table 1. Comparisons of three kinds of biomass curing equipment

Equipment	Productivity	Energy Consumption	Abrasion
Screw extrusion forming machine	Low	High	Severe
Piston punch forming machine	Low	Low	Severe
Die roll forming machine	High	High	Severe

3. Structure and Working Principle

3.1 Structure

The bidirectional screw extrusion biomass honeycomb briquette machine mainly consists of two major parts: the screw extrusion section and the extrusion moulding section. The screw extrusion section includes a unidirectional motor, couplings, a reducer, a feeding device, and a moulding sleeve, among other components. The extrusion moulding section mainly includes a bidirectional motor, couplings, a reducer, and a crank-slider mechanism, as shown in Figure 2.



1. Unidirectional motor; 2. Reducer; 3. Feeding device; 4. Moulding sleeve; 5. Bolt; 6. Coupling; 7. Base; 8. Connecting rod; 9. Crank; 10. Slider; 11. Bidirectional motor

Figure 2: Bidirectional screw extrusion biomass honeycomb briquette machine

3.2 Working Principle

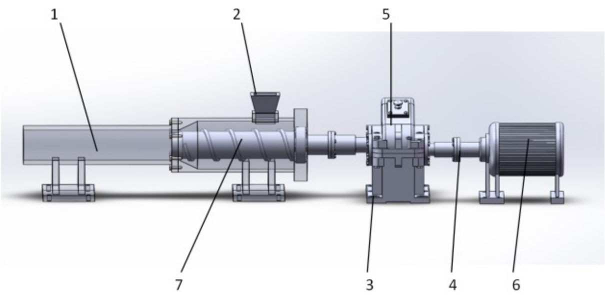
During operation, the crushed biomass material enters the machine body from the feeding devices on both sides under the action of gravity. Each side of the briquette machine is driven by a unidirectional motor to transport the biomass material into the moulding sleeve via a screw. At this point, the biomass material is continuously pushed and compressed within the moulding sleeve by the screw.

Meanwhile, the bidirectional motor drives the slider to the opposite end inside the moulding sleeve. The slider briefly stays within the extrusion sleeve, where it works in conjunction with the screw extrusion device to compress the biomass material. Since the slider is uniformly equipped with punching pins, the biomass material is compressed into a honeycomb shape. After the extrusion moulding is complete, the slider exits the moulding sleeve, and the moulded honeycomb-shaped biomass densified fuels is pushed out of the moulding sleeve. The process then proceeds to the next cycle.

4. Design of Screw Extrusion Device

4.1 Structure and Working Principle of the Screw Extrusion Device

The screw extrusion device is an indispensable component of the bidirectional screw extrusion biomass honeycomb briquette machine. It mainly consists of a unidirectional motor, reducer, coupling, extrusion screw, extrusion sleeve, and other components, as shown in Figure 3. During the biomass honeycomb briquette moulding process, the screw extrusion device primarily serves the functions of conveying and compressing the material. Additionally, the screw extrusion method offers advantages such as smooth transport and continuous material feeding.



1. Moulding sleeve; 2. Feed inlet; 3. Bolt; 4. Coupling; 5. Reducer; 6. Motor; 7. Screw

Figure 3: Screw extrusion device

The output end of the motor on the right side of the screw extrusion device is connected to the reducer via a coupling, and the output end of the reducer is connected to the screw via another coupling. When the right-side motor is powered on, it drives the reducer to operate. Once the speed of the reducer reaches a certain requirement, it drives the screw to rotate. As the crushed biomass material enters the machine body through the feed inlet, it is pushed into the moulding sleeve by the continuously rotating screw. As the amount of material in the moulding sleeve increases, the pushing action of the screw is simultaneously converted into a compressive force, causing the material to be compressed and moulded inside the moulding sleeve.

4.2 Selection of Motor and Reducer

Given that the required total output of the briquette machine is Q=200 kg/h(i.e., the unidirectional output Q_1=100 kg/h), and the specific power consumption is S=40 kg/kW·h, the required power for the briquette machine is calculated as follows:

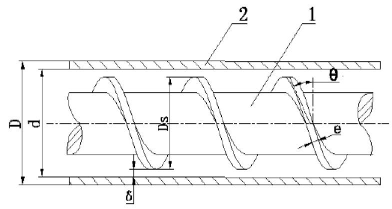
$$P_1 = \frac{Q_1}{S} \tag{1}$$

After calculation, P_1=2.5kW, so the motor model is selected as Y132S-6, with a rated power of P_1=3kW, a speed of n_1=960r/min, and an efficiency of η=83% [20].

The chosen reducer model is BWD10-17-0.5-B3.

4.3 Design of the Extrusion Device

The main structure of the extrusion device consists of two parts. The first part is the extrusion screw, and the second part is the extrusion sleeve. The extrusion of the biomass is achieved through the cooperation of these two components, as shown in Figure 4.



1. Extrusion screw; 2. Extrusion sleeve

Figure 4: Screw and sleeve

(1) Design of the Extrusion Screw

1) Determination of the screw diameter Ds.

The selection of the screw diameter is related to the rotational speed. In actual production, after the screw speed is determined, the diameter of the extrusion screw on one side can be derived from Equation (2):

$$Q = 2\beta D_s^3 n \tag{2}$$

Where, Q is the production capacity in kg/h; D_s is the screw diameter in mm; n is the screw rotational speed in r/min; β is the discharge coefficient, typically ranging from 0.000003 to 0.000007.

Due to the lignin in the material, which gives it a certain viscosity and makes it prone to adhering to the screw, a smaller value for β is chosen. Therefore, β=0.000003, and the screw diameter D_s is calculated to be 82.2 mm. Given that the screw series diameters are 30, 45, 65, 90, 120, 135, 150, 160, 200 mm, the selected extrusion screw diameter is D_s=90 mm [21].

2) Determination of the Length-to-Diameter Ratio L/D_s

In daily production, the length-to-diameter ratio of the extrusion screw is generally fixed. This means that once the screw diameter is determined, the length can be adjusted to achieve the desired length-to-diameter ratio, making the screw longer. When the screw reaches a certain length, the material stays inside the moulding sleeve for a longer period, making it easier to compress and mould. However, if the length-to-diameter ratio is too large, it becomes inconvenient for screw installation, and more energy is consumed during machine start-up. The determination of the length-to-diameter ratio L/D_s is based on both the intrinsic factors of the production process and external environmental factors. The chosen length-to-diameter ratio is S=4, with the extrusion screw length L=360 mm.

3) Determination of Other Screw Parameters

The width of the screw thread e is generally taken as $e=(0.08-0.12)D_s$. If the screw thread width e is too small, the strength of the screw will be insufficient. On the other hand, if the thread width is too large, the capacity will be reduced. Therefore, various factors must be considered to determine the screw thread width. The chosen width is e=10 mm.

4) Strength Verification of the Extrusion Screw

① Taking the right extrusion screw as an example, the material pressure acting on the screw during extrusion can be approximated as the pressure applied at the left end of the screw. The resulting shrinkage stress is denoted as σ_c. The force F can be calculated using the following formula:

$$F=(1.125-1.25)\times\frac{\pi}{4}\emptyset^2P \tag{3}$$

Where, F is the material extrusion pressure in N; ϕ is the diameter of the honeycomb briquette in mm; P is the pressure exerted on the screw in MPa.

According to relevant data, the required pressure ranges from 1 MPa to 6 MPa. To facilitate the moulding of honeycomb briquettes, the pressure p is chosen to be 6 MPa, with a coefficient of 1.25, and ϕ=100 mm. The required moulding force can be calculated that F=5.89×104 N.

The shrinkage stress σ_c can be calculated from Equation (4):

$$\sigma_c=\frac{F}{\frac{\pi}{4}{d_0}^3} \tag{4}$$

Where, F is the material extrusion stress in N; d_0 is the root diameter of the screw in mm. By calculation, the compressive stress σ_c generated by the material pressure P is 9.56 MPa.

② During the extrusion process, the shear stress exerted on the screw can be calculated using the following formula:

$$\tau=\frac{T}{W_s}=\frac{9.55\times10^6\frac{P}{n}\times\eta}{\frac{\pi}{16}{D_s}^3\ (1-C^4)} \tag{5}$$

Where, τ is the shear stress in MPa; T is the torque from the motor in N·mm; W_s is the screw's torsional section modulus in mm^3; n is the screw rotational speed in r/min; η is the extrusion transmission efficiency.

D_s is the outer diameter of the extrusion screw in mm; C is determined by d_0/D_s. By calculation, the shear stress τ generated by the torque T is 4.4 MPa.

③ During operation, the material will fill the gap between the extrusion screw and the sleeve. Therefore, the bending stress caused by the screw's weight can be neglected in the calculations.

④ The resultant stress σ_r of the extrusion screw is given by:

$$\sigma_{r=}\sqrt{{\sigma_c}^2+4\tau} \tag{6}$$

Where, σ_r is the resultant stress in MPa; σ_c is the compressive stress in MPa; τ is the torsional shear stress in MPa.

The resultant stress σ_r is calculated as 14.52 MPa, which is less than the allowable stress [σ]=25 MPa, thus meeting the required specifications. Here, [σ] refers to the allowable stress for the extrusion screw.

(2) Design of the Extrusion Sleeve

The extrusion system is a crucial component of the briquette machine, and the extrusion system consists of two parts: the screw and the moulding sleeve. Through the cooperation of these two parts, the entire moulding process is completed, including material transport, extrusion, and moulding. Therefore, the design of the extrusion sleeve body directly determines the quality of the moulded product and is a critical component of the extrusion system.

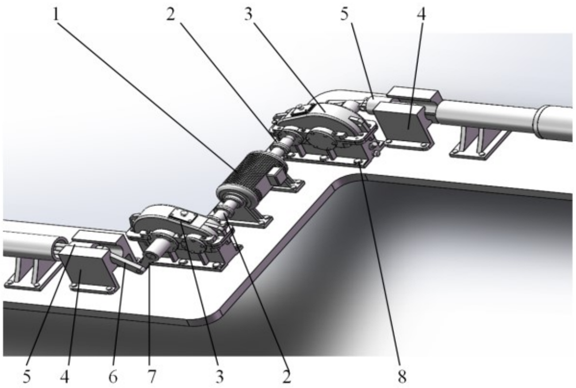
The extrusion screw and extrusion sleeve must work in close coordination. The gap precision between the screw and the sleeve is extremely important, as it significantly affects the moulding process. A larger gap δ makes it easier for the screw and sleeve to mesh, but the material may stay in the sleeve for too long, which negatively impacts the moulding efficiency. On the other hand, a smaller gap δ increases the difficulty of installation and production, and it also leads to higher energy consumption during operation. Based on experience, a gap of δ=10 mm is chosen. The sleeve wall thickness is set at 10 mm, giving the sleeve an outer diameter D=130 mm, an inner diameter d=110 mm, and a length L=460 mm.

5. Design of the Moulding Device

5.1 Structure and Working Principle of the Moulding Device

The moulding device is an important component of the bidirectional screw extrusion biomass honeycomb briquette machine. It is driven by a bidirectional motor, which moves the crankshaft to achieve the reciprocating motion of the sliders on both sides. The main function of the moulding device is to compress the biomass material and mould it into a honeycomb shape with five 20 mm holes. The biomass briquettes with holes can burn more efficiently, allowing for complete combustion.

As shown in Figure 5, the moulding device is driven by a bidirectional motor, which is connected to the reducers on both sides via couplings. The output of the reducers is then connected to the crank-slider mechanism. During operation, the motor drives the reducers, which in turn drive the crank-slider mechanism. When the slider moves into the extrusion sleeve, it briefly stays inside the sleeve while the screw continues to push the material toward the slider, completing the extrusion moulding of the biomass. During this process, the slider needs to work in coordination with the screw extrusion device to achieve the compression and moulding of the material.

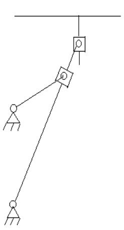


1. Bidirectional motor; 2. Coupling; 3. Reducer; 4. Track; 5. Slider; 6. Connecting rod; 7. Crank; 8. Bolt

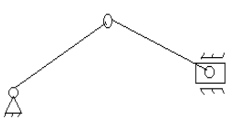
Figure 5: Moulding device

5.2 Scheme Selection and Analysis

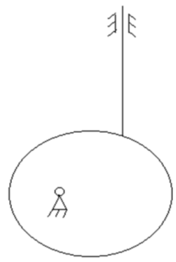
Analysing Figure 6, although Scheme (a) has many components, it is not conducive to production as it may get stuck. Scheme (c) has a cam mechanism that can move back and forth, but achieves vertical motion. Scheme (b) is the most suitable choice, with a very simple structure, stable performance, and minimal energy loss, so scheme (b) is chosen.



(a) Guide rod-slider mechanism



(b) Crank-slider mechanism



(c) Cam mechanism

Figure 6: 3 punching mechanism schemes

5.3 Data Calculation of the Moulding Mechanism

As shown in Figure 7, the design adopts a concentric crank-slider mechanism [22-24]. In this mechanism, the hinge centres of the crank and slider on the crank-slider mechanism lie on the same horizontal line, meaning that there is no “dead-centre” characteristic.

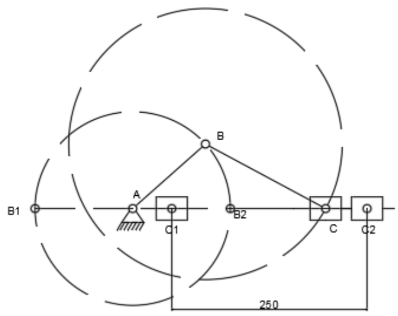


Figure 7: Crank-slider mechanism

The lengths of the crank and connecting rod are as follows:

AB（A1B1、A2B2）=125mm

BC（B1C1、B2C2）=175mm

As shown in Figure 5, the two extreme positions of the crank are B1 and B2. The corresponding extreme positions of the slider define the slider's stroke. To determine this, first draw a horizontal extension line through point A. Then, using point A as the centre, draw a circle with radius AB, creating the first circle. Select an arbitrary point on this circle, labelled as point B. Next, using point B as the centre, draw a second circle with radius BC. This second circle intersects the horizontal extension line from point A at a point labelled as C. The position of point C is the midpoint of the slider's hinge.

Determination of the Extreme Positions of the Slider (C1, C2):

Since the crank-slider mechanism is concentric, the trajectories of the crank, the extreme positions of the slider, and the extreme positions of the two cranks (B1, B2) all lie on the horizontal extension line through point A. The circle with radius AB, drawn previously, intersects the horizontal extension line through point A at two points, B1 and

B2. Then, using the length of BC as the standard extension line B1A, the point C1, found through this method, is one extreme position of the slider. Similarly, for B2, the length of BC is used as the standard extension line, and the point C2 is found. The measured length of C1C2 is the stroke of the slider. The measured value is C1C2=250 mm.

The positions of B1, C1, B2, and C2 define the slider stroke, as shown in Figure 7.

Since the production rate is 200 kg/h, the unidirectional production rate is 100 kg/h. The slider moves reciprocally, and during each stroke, it can only compress one briquette. Using the formula $m=\rho\cdot v$, where the biomass moulding density is between 1.0 g/cm^3 and 1.4 g/cm^3, and the honeycomb briquette has five 20 mm diameter holes, the total diameter is ϕ=100 mm and the height h=100 mm, the volume of the honeycomb briquette can be calculated as v=775 cm^3. Given the unidirectional production rate of 100 kg/h and the mass of one honeycomb briquette being 775 g, it is known that the slider needs to move back and forth 129 times per hour for one side. The crank speed is n=129 r/h (n=2.15 r/min).

5.4 Selection of the Motor and Reducer for the Moulding Mechanism

The unidirectional crank speed is 129 r/h, so the selected bidirectional motor model is YB3-80M2-2, with a rated power of P=6 kW/h, speed n=1500 r/min, and efficiency η=83%.

The selected cycloidal needle wheel reducer model is BWD5/BLD5-7.5.

6. Conclusions

A bidirectional screw extrusion biomass honeycomb briquette moulding machine has been designed. This machine can compress the crushed biomass material into a honeycomb briquette shape, increasing the effective contact area between the biomass densified fuel and oxygen. Additionally, the moulding machine uses a bidirectional motor to drive the extrusion moulding devices on both sides, effectively improving the production rate of biomass densified fuels.

References

[1] Yunusa, S. U., Mensah, E., Preko, K., Narra, S., Saleh, A., & Sanfo, S. (2024). A comprehensive review on the technical aspects of biomass briquetting. Biomass Conversion and Biorefinery, 14(18), 21619-21644.

[2] Huang, H., Gao, Y., Chen, H., Wu, Y., Wang, J., Yu, C., Li, J., & Zou, C. (2023). Biomass briquette fuel, boiler types and pollutant emissions of industrial biomass boiler: A review. Particuology, 77, 79-90.

[3] Li, Z., Li, Z. Q., Zhang, D. H., & Yue, Q. (2023). Characterization of dense forming force chain of salix granules under uniaxial compression. Journal of Forestry Engineering, 8(2),124-130.

[4] Vaish, S., Sharma, N. K., & Kaur, G. (2022). A review on various types of densification/briquetting technologies of biomass residues. IOP conference series: materials science and engineering,1228(1), 012019.

[5] Liang, F. M., Jiao, J., Zhu, B. P., Deng, Y. J., & Fang, G. G. (2023). Effects of two different mechanical pretreatment methods on reactivity of biomass raw materials. Journal of Forestry Engineering, 8(2),117-123.

[6] Sarker, T. R., Nanda, S., Dalai, A. K., & Meda, V. (2021). A review of torrefaction technology for upgrading lignocellulosic biomass to solid biofuels. BioEnergy Research, 14, 645-669.

[7] Malik, M. A. I., Mujtaba, M. A., Kalam, M. A., Silitonga, A. S., & Ikram, A. (2024). Recent advances in hydrogen supplementation to promote biomass fuels for reducing greenhouse gases. International Journal of Hydrogen Energy, 49, 463-487.

[8] Inegbediona, F., & Francis-Akilaki, T. I. (2022). Design and Fabrication of a briquetting machine. Journal of Energy Technology and Environment, 4(1),11-20.

[9] Xiang, Y., Liu, M., Shi, L., Zhang, N., & Niu, Z. (2017). Design and Text of Biochar Screw Extrusion Molding Machine. Journal of Huazhong Agricultural University, 36(5), 115-120.

[10] Wang, W., Zhou, G., Cai, D., Zheng, Q., Li, Z., Liu, L., & Chen, L. (2023). Design and experiment of the biomass briquetting machine with honeycomb structure bionic ring-die. Transactions of the Chinese Society of Agricultural Engineering, 39(17), 267-274.

[11] Di M., Huang Y., Chen Y., Gao W., Yang J., & Li Y. (2024). Biomass Molding Technology and Design of LH-600 Biomass Granulation Molding Machine. Agricultural Engineering,14(1), 89-94.

[12] Wu G., Liu Y., Lv F., & Li B. (2017). Optimum design of the molding drum of the piston punch biomass briquetting machine. Journal of Henan Agricultural University, 51(3):341-347+369.

[13] Cai, H., Liu, J., Cheng, W., Yi, W., Jiang, X., & Gao, F. (2020). Design and Experiment of Epicyclic Train Structured Biomass Ring-die Briquetting Machine with Plunger Roller. Transactions of the Chinese Society for Agricultural Machinery, 51(S2), 435-441.

[14] Cheng J., & Jiang J. (2024). Design and study of a spiral extruding camellia oleifera fruit sheller with adjustable screen roll gap. Packaging & Food Machinery, 42(3), 76-83+90.

[15] Lewandowski, A., & Wilczyński, K. (2022). Modeling of twin screw extrusion of polymeric materials. Polymers, 14(2), 274.

[16] Zhang Y., & Wang B. (2024). Modeling and optimization of surface roughness for milling medium density fiberboard with single edge helical milling cutter. Journal of Forestry Engineering,9(3):61-68.

[17] Ning T., & Qian X. (2023). Design and kinematics analysis of vertical external meshing biomass pellet fuel forming machine. International Journal of Mechatronics and Applied Mechanics, (13), 30-37.

[18] Zhang, J., De, X., Li, Z., Guo, W., & Yu, L. (2020). Current Status of Research on Biomass Curing Mechanism and Equipment. China Forest Products Industry, 57(12), 45-49.

[19] Ning, T., Liu, P., & Hou, S. (2017). The biomass curing equipment and the analysis of its forming influence factors. Renewable Energy Resources, 35(1), 135-140.

[20] GB 18613-2020. (2020). Minimum allowable values of energy efficiency and values of efficiency grades for motors. Beijing: Chemical Industry Press.

[21] JB/T 8061-2011. (2011). Plastics single-screw extruder. Beijing: China Machine Press.

[22] Wang, Q., Li, A., Gao, L., Wei, Q., Wu, M., Zhao, Y., & Zheng, Z. (2024). Design and Testing of Reciprocating Chrysanthemum morifolium Picking Device. Transactions of the Chinese Society for Agricultural Machinery, 55(s2), 95-103, 199.

[23] Zhang, F., Wu, Z., Dong, Y., Sun, H., Zhang, Z. (2023). Structure Design and Simulation of Multi-terrain Planter Turnover Device Based on Crank Slider Mechanism. Modern Manufacturing Technology and Equipment, 59(6), 195-197.

[24] Xiao, J., Sun, L. (2024). Mechanism Analysis and Simulation of the Dough Kneading Machine Based on VB. Machinery, 51(11), 64-70.