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Analysis of the Crushing Mechanism of Kitchen Waste and Simulation Design of Crushing Structure Optimization

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Abstract. This article conducts research on the treatment of kitchen waste. The treatment of kitchen waste includes front-end, mid-range, and back-end. The main focus of this article is on the front-end treatment process, which is how to design a more efficient and reasonable kitchen waste crusher for front-end treatment of waste crushing. Therefore, this article first establishes the model structure of kitchen waste and the crushing boundary conditions of kitchen waste. Based on the boundary conditions and mathematical models, the research on the crushing mechanism of the crusher and the design of the crusher structure are completed. For the structure of the crusher, the main parameters that determine the crushing effect, such as the shape of the crusher roller teeth, the size of the roller tooth structure, and the intersection angle of the roller teeth, are optimized. Finally, the structure optimization of the crusher gear and the crusher tooth roller is determined through simulation and discrete analysis of the three-dimensional model.

Keywords: kitchen waste, crusher, crushing mechanism, parameter optimization

1 Introduction

With the continuous development of urbanization, the problem of urban household waste disposal is becoming increasingly prominent. Garbage disposal is not only a social problem but also a technical problem. To solve this problem, in addition to sound laws and regulations, specific and executable technical means are also necessary.

Kitchen waste usually refers to food related waste generated in daily life, such as food processing in the catering industry, cooking processes for residents, and waste generated during the meal supply process of units, including perishable waste such as the skin of various fruits and vegetables, animal organs, bones, fur, shells, leftovers, and rice [1]. The existing methods for treating kitchen waste are usually divided into physical, biological, and chemical methods. Specific treatment methods include crushing and direct discharge treatment, earthworm composting, anaerobic treatment, microbial cell treatment, incineration treatment, feed conversion treatment, and fertilizer making treatment. The most commonly used method among the above is anaerobic digestion treatment. In addition, saprophytic biological treatment, composting treatment, mechanical treatment, etc. are also common methods for kitchen waste treatment [2].

Summarizing the process of kitchen waste treatment, it can generally be divided into three processing steps: front-end, terminal, and back-end. The focus of the entire process should be on the front-end processing of kitchen waste. Only when the front-end process of waste treatment is efficient can the maximization of waste recycling be achieved, thereby achieving the goal of harmless treatment of household waste. The so-called front-end treatment of kitchen waste, from the perspective of domestic and foreign as well as current treatment methods, the most effective and reliable treatment method is crushing. The main equipment for crushing is the kitchen waste crusher. Therefore, the main research content of this article is the crushing mechanism of the crusher, as well as the optimization design of the crusher and the establishment of a scientific finite element analysis model [3].

The main research focus of this article is to solve the following problems of current crushers:

1) The design index parameters of the crusher are too high, resulting in material and cost waste. The root cause is the use of empirical methods in the design process, which did not fully model and analyze the crushing object.

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2) The design structure of the crusher is unreasonable, and different crushing angles and numbers of teeth of the double toothed roller crusher can lead to different crushing effects. Similarly, in the past, the design of the number of teeth and angles of crushers also used empirical methods.

Therefore, the work done in this article is as follows:

1) By analyzing the composition and generation methods of kitchen waste, an effective mathematical model that can reflect kitchen waste to the maximum extent possible and accurately is established, which facilitates the design and analysis of crushers.

2) A three-dimensional model of the garbage crusher was established, and finite element analysis was used to optimize the parameters of the three-dimensional model, in order to obtain the optimal parameters for each structure of the crusher.

3) Considering the urban waste treatment process, this equipment will be arranged in the community, where the concentrated kitchen waste will be collected and crushed before proceeding to the next step of treatment.

2 Manuscript Preparation

Many scholars have conducted research on the treatment of kitchen waste, and the research object of this article is the crushing mechanism. Therefore, the comparative analysis mainly focuses on the front-end of the treatment, that is, the study of garbage crushing equipment.

Gang Song from the Agricultural Machinery Research Institute of the Chinese Academy of Tropical Agricultural Sciences believes that the best effect is achieved at a tooth roller speed of 35 r/min and a material drop height of 230 mm. He used modeling of a double tooth roller crusher to simulate the crushing of kitchen waste represented by bones, and observed the corresponding effects of changing the tooth roller speed n and material drop height h [4].

Shuo Feng designed an integrated kitchen waste treatment device to meet the actual needs of kitchen waste treatment. The core structure of the device is a variable pitch screw extrusion device. The parameters of each component are determined through design and calculation. The SolidWorks Simulation module is used to perform finite element analysis on the screw rod of the screw extrusion, and then the strength and stiffness of the main components of the device are verified to improve the dehydration rate of the equipment [5].

Similarly, with regard to spiral extrusion, Jinpan's Chang research objective is to obtain a variable diameter and pitch spiral extrusion device, in order to achieve better extrusion effects on kitchen waste. Through finite element analysis of the spiral blades, including model design, size parameter design, model optimization, model introduction, material selection, mesh division, force analysis, stress analysis of the spiral blades in equal and variable axis diameters, and optimization design of the rotating spindle, the ideal variable diameter and pitch variable axis diameter spiral extrusion device was ultimately obtained [6].

Yuhan Xu, in response to the current situation of urban development in China, as well as the increasing number of urban residents and the increasingly prominent problem of urban waste treatment, this study designs an intelligent treatment equipment for kitchen waste, which realizes functions such as dry and wet separation, solid carbonization, liquid-liquid separation and recycling of kitchen waste, and can effectively solve the problems of automatic classification and recycling of kitchen waste [7].

Fu Xin proposed a new method of integrating multi-stage differential crushing and shaping for the front-end stage of waste treatment, and designed a multi-stage crushing and shaping machine for household waste. Analyzed the design principle and structural composition of the all-in-one machine, and analyzed the design of key components in the all-in-one machine. After design and analysis, the all-in-one machine can ultimately achieve step-by-step crushing and shaping of household waste containing a mixture of soft and hard materials [8].

Bin Zhu from Shanghai University of Technology has designed a crusher with a different tooth structure, aimed at solving the problems of low crushing efficiency and incomplete crushing of hard waste such as pig bones and cow bones in the double tooth roller crusher. Analyze the structural design and advantages of the different tooth crusher, determine the tool clearance and center distance, as well as the characteristics of the tool tooth arrangement [9].

Guihua Lin, in response to the phenomenon of luxury cruise ships generating a large amount of kitchen waste during each voyage, designs a kitchen waste disposal system. This system uses a new type of kitchen waste crushing and dewatering integrated machine that combines a helical cylindrical gear grinding roller crushing method and a microwave drying and dewatering method, and studies the vacuum compression treatment process after dehydration. Based on CATIA software, the garbage crushing and dewatering integrated machine and vacuum compression device were modeled, and the contact finite element analysis of the gear grinding roller of the crushing device was carried out using Workbench software to verify the feasibility of the crushing device design. The analysis of roller teeth and the idea of finite element modeling have good reference significance for this article. Its ship application scenario can be seen as a miniaturized community [10].

Yubo Hu from China University of Geosciences, aiming at the problems of high cost, large floor space and failure to meet the emission standards of the existing wet waste treatment device nearby, a new type of mechanical compressive wet waste treatment device is developed. Firstly, the functions and technical characteristics of the mechanical compressive wet waste treatment device were introduced. Then, the modular design of the mechanical compressive wet waste treatment device was carried out, which mainly included the lifting device, the conveyor belt sorting device, the crushing and dewatering device, the sewage treatment device and the briquetting device. Finally, the technical parameters of the mechanical compressive wet waste treatment device were designed and calculated, and its automatic control scheme was designed. The designed mechanical compressive wet waste treatment device integrated the traditional waste crusher and the press dehydrator to realize the efficient dehydration of the wet waste; through the treatment of the briquetting device, the compression of the waste residue was realized, which could effectively relieve the problems of tight capacity and secondary pollution in the waste transportation; by the treatment of the sewage treatment device, the recycling and reuse of sewage was realized. The mechanical compressive wet waste treatment device has the advantages of low cost, small volume, simple treatment process and less labor resource consumption. It is suitable for small and medium-sized waste collection stations that have implemented waste classification and collection, and has broad market prospects in the wet waste treatment industry [11].

After the above analysis, it is necessary to design specialized crushing equipment for the crushing of kitchen waste. The design of the equipment's cutting tools and rollers is the core part of its optimization. Analyzing the double roller rotation mechanism can help establish a crushing model. Then, the idea of this article is to construct a model of community kitchen waste, analyze the force on the waste, establish a crushing equipment model, construct a finite element analysis model of the equipment, optimize the parameters of the roller teeth and roller structure, and calculate the garbage treatment capacity after optimization.

3 Establishment of Analysis Model for Kitchen Waste

Kitchen waste is the working object of the crusher, so establishing a real waste model can help analyze the process of tool crushing and establish a more reasonable tool model. Therefore, this section will conduct modeling and analysis based on the composition of the waste and the force mode of the waste.

3.1 Analysis of Kitchen Waste Components and Selection of Treatment Processes

The garbage dealt with in this article is mainly kitchen waste, which is generated in daily household life. It mainly consists of perishable organic waste such as fruits, vegetables, food scraps, leftover food, and fruit peels discarded in daily household life. In addition, organic waste such as discarded rotten fruits, vegetables, fish, poultry and other animal organs is also the main source of kitchen waste.

The composition characteristics of kitchen waste are greatly influenced by the classification of waste. In areas where garbage classification is not implemented, the proportion of debris is nearly 40%, mainly plastic, paper, fabric, metal, etc. Occasionally, there may be large debris. The moisture content of garbage is about 55%~65%, and it basically does not contain oil. During the 13th Five Year Plan period, the garbage classification policy was gradually implemented, and some key cities such as Shanghai, Hangzhou, Xiamen, etc. took the lead in implementing garbage classification. The composition characteristics of kitchen waste also changed accordingly. With the advancement of garbage classification, the organic matter content of kitchen waste has significantly increased, while the impurity content has significantly decreased. At present, the organic matter content of kitchen waste in areas where garbage classification is implemented is over 85%, with a moisture content of over 75%, and it contains about 1.5% oil and fat. Its nature is closer to kitchen waste, but it also has different properties compared to kitchen waste. Kitchen waste mainly consists of "raw materials", which have a higher cellulose content and poorer biodegradability compared to cooked food waste [12].

In order to make the crusher structure designed in this article more reasonable, with higher crushing efficiency and stronger crushing capacity, it is necessary to analyze the main areas where the crushing equipment designed in this article is placed, as well as the detailed composition of kitchen waste in the placement area. Due to the targeted focus of energy and research scope, as well as the source of financial support, the research scope of this article mainly focuses on Tianjin, Hebei and other regions. Therefore, in order to ensure the rationality of the scope, the main deployment area of kitchen waste crushing equipment is set to the North China region.

The main staple food on the dining table in North China is a combination of rice and pasta, while meat is mainly chicken, duck, fish, and pig, and seafood also accounts for a certain proportion. Therefore, it is necessary to conduct sampling and analysis of the composition of kitchen waste generated in the field within North China. Five representative communities in North China are randomly selected, such as Lijing Qinyuan Community in Tangshan, Wellington Community in Tianjin, Tiantongyuan Community in Beijing, Wanke Park Avenue Community in Shijiazhuang, and Jinqiao Park No.1 Community in Tianjin. The composition of kitchen waste generated by these five communities every day is observed and recorded, with an observation period of one month. Through one month of observation and recording, the screening and identification of the composition categories of kitchen waste samples are completed, and the basic physical properties are calculated, providing data support for subsequent discrete finite element simulation of kitchen waste fragmentation. Use tweezers to pick up or simply classify the kitchen waste collected for sample preparation, and then make a basic classification with the naked eye. The classification does not need to be particularly detailed, and the purpose of classification is to put together similar components. It can be roughly divided into five categories: rice, crushed bones and meat, fruit peels, vegetable waste, and inorganic substances. Number each community as a group, use electronic scales and tweezers to sort and weigh each type within the five groups, calculate the percentage of each constituent group, and finally take the average value as a representative of the sample proportion.

The process of garbage disposal is very strong, usually from the generation of garbage to its final destination, and the entire process can adopt effective treatment techniques. To achieve the goal of economic, universal, and harmless treatment and utilization of kitchen waste, a reasonable and scientific treatment process route should be developed. A reasonable and effective garbage treatment route must be based on the existing mature garbage treatment processes, so it is necessary to summarize and analyze the existing garbage treatment methods. The awareness of exploring green treatment processes and techniques for the reuse of kitchen waste in China is relatively late compared to developed countries, and the advanced technologies currently used are basically learned and borrowed from European and American countries. Currently, only first tier cities such as Beijing, Shanghai, Guangzhou, and Shenzhen have adopted the “garbage classification” policy and large-scale centralized treatment technology as the main treatment methods for kitchen waste, and spare no effort in promoting new technologies for kitchen waste resources.

The typical treatment processes for existing kitchen waste include incineration, landfill, crushing and direct discharge, drying and oil removal processes, and microbial composting processes. Their respective processing processes and advantages and disadvantages are as follows: incineration and landfill methods sacrifice environmental resources and damage the environment at the cost. Although they can achieve the most direct and efficient treatment results, their environmental drawbacks are too prominent, which has led to the gradual withdrawal of these two processes from the historical stage. The crushing and direct discharge process originated in European and American countries. The operation method is to install a three-stage high-speed crusher at the lower end of the washing basin. After crushing, the kitchen waste is directly crushed into particles with a diameter of less than 2 millimeters using the water flow in the kitchen faucet, which is directly flushed into the drainage pipeline. This can efficiently treat kitchen waste in real time. However, such treatment equipment is generally expensive, and it is not feasible for households to purchase similar equipment actively in China. In addition, the kitchen waste discharged into groundwater will inevitably have an impact on surrounding underground resources.

Therefore, summarizing advanced foreign experience and combining with the current situation of kitchen waste treatment, this article uses the crushing method to treat kitchen waste. Firstly, let’s take a look at the conventional process of domestic waste treatment, as shown in Fig. 1.

In order to improve the treatment efficiency of kitchen waste, this article increases the crushing process of kitchen waste in the generation and reception of kitchen waste. The generated kitchen waste is treated on site, and the equipment is arranged in the corresponding places in the community. After collecting all kitchen waste in the community, it is uniformly crushed and processed [13].

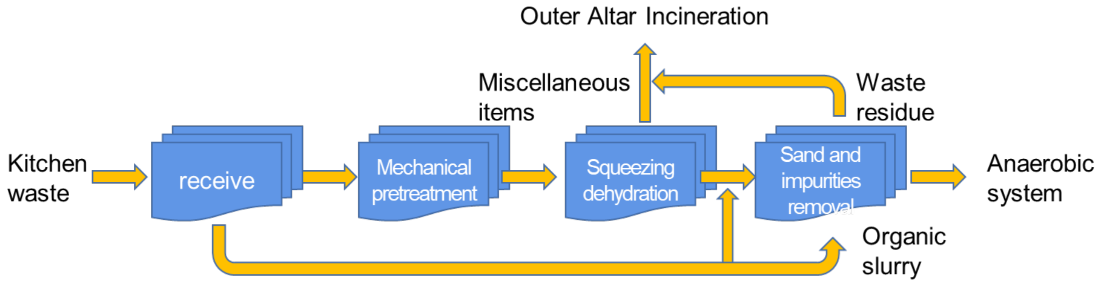


Fig. 1. Kitchen waste treatment process

3.2 Analysis of Force on Kitchen Waste

In order to analyze the crushing mechanism of the crusher and improve the crushing effect in the following chapter, it is necessary to conduct a force analysis on kitchen waste. According to 3.1, the composition and proportion of waste vary in different regions and seasons, and the complex composition structure and size differences of different waste lead to differences in their physical and mechanical properties. Kitchen waste in the community is generally wrapped in garbage bags or convenience bags [14]. Therefore, in order to facilitate research, it must be abstracted as a mechanical model that can be used for mechanical research. Therefore, the following assumptions are made about kitchen waste:

(1) Only considering garbage as a macro whole and macro composition, ignoring the differences in garbage composition caused by regional differences.

(2) Consider kitchen waste as a regular geometric body as a whole, and the cross-section as a cylindrical section. Do not consider the protruding and hard domestic waste present in individual waste compositions, and treat the processed kitchen waste object as an elastic cylindrical body.

(3) Considering macro characteristics, consider kitchen waste as a whole as a transversely isotropic material.

(4) During the on-site treatment of kitchen waste, its macroscopic mechanical properties are consistent, with each part tightly connected and each component arranged neatly along the axis without relative displacement.

The stress-strain relationship of isotropic materials can be represented by the generalized Hooke's law, while the stress-strain relationship of anisotropic materials is expressed as:

$$\begin{bmatrix} \tau_{12} \\ \tau_{31} \\ \tau_{23} \\ \sigma_3 \\ \sigma_2 \\ \sigma_1 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66} \end{bmatrix} \begin{bmatrix} \gamma_{12} \\ \gamma_{31} \\ \gamma_{23} \\ \varepsilon_3 \\ \varepsilon_2 \\ \varepsilon_1 \end{bmatrix}. \tag{1}$$

In the formula, $\sigma_i = c_{ij}\varepsilon_j (i, j = 1, 2, \cdots, 6)$, where σ_i is the stress component, c_{ij} is the stiffness coefficient, and ε_j is the engineering strain component. 36 elastic parameters are needed to express his stress-strain relationship.

Orthogonal anisotropic body refers to a material with three mutually perpendicular planes, in which the mechanical properties of the material are different in different directions. If one of the planes has the properties of isotropic materials, that is, the mechanical properties of the plane are the same in all directions, and the other two faces perpendicular to it have anisotropic properties, then the elastic body is called a transversely isotropic body. A plane with the properties of isotropic materials is called an isotropic plane, and the flexibility matrix of transversely isotropic materials can be represented by 12 engineering constants. The flexibility matrix is represented as follows:

$$[S]=\begin{bmatrix} \frac{1}{E_x} & \frac{-\mu_{yx}}{E_y} & \frac{-\mu_{zx}}{E_z} & 0 & 0 & 0 \\ \frac{-\mu_{xy}}{E_x} & \frac{1}{E_y} & \frac{-\mu_{zy}}{E_z} & 0 & 0 & 0 \\ \frac{-\mu_{xz}}{E_x} & \frac{-\mu_{yz}}{E_z} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{zx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix}. \tag{2}$$

In the formula, E_x, E_y, and E_z are the axial elastic moduli along three mutually perpendicular coordinate axes, $E_y = E_x$, G_{xy}, G_{yz}, and G_{zx} are the shear moduli in the xy plane, yz plane, and xz plane, $G_{yz} = G_{zx}$, μ_{xy}, μ_{yz}, and μ_{zx} are Poisson's ratios, and $\mu_{yz} = \mu_{zx}$.

$$\mu_{ij} = -\frac{\varepsilon_j}{\varepsilon_i}. \tag{3}$$

By combining the above formulas, the following formula is obtained:

$$\begin{cases} c_{11} = \dfrac{1-\mu_{yz}\mu_{zy}}{E_y} \\ c_{12} = \dfrac{\mu_{xy}+\mu_{xz}\mu_{zy}}{E_z} = \dfrac{\mu_{yx}+\mu_{yz}\mu_{zx}}{E_x} = c_{21} \\ c_{13} = \dfrac{\mu_{xz}+\mu_{xy}\mu_{zy}}{E_x} = \dfrac{\mu_{zx}+\mu_{yx}\mu_{zy}}{E_y} = c_{31} \\ c_{22} = \dfrac{1+\mu_{xz}\mu_{zx}}{E_z} \\ c_{33} = \dfrac{1+\mu_{xy}\mu_{yx}}{E_y} \\ c_{44} = G_{zx} \\ c_{66} = G_{xy} \end{cases}. \tag{4}$$

3.3 Elastic Mechanics Model of Kitchen Waste

From the above analysis, it can be seen that kitchen waste can be regarded as a transversely isotropic body based on its structural characteristics [15]. Express the constitutive equation of kitchen waste using engineering constants:

$$\begin{cases} \varepsilon_r = \dfrac{1}{E_1}\left(\sigma_r - \mu_1\sigma_\theta\right) - \dfrac{v_2}{E_2}\sigma_z \\ \varepsilon_\theta = \dfrac{1}{E_1}\left(\sigma_\theta - \mu_1\sigma_r\right) - \dfrac{v_2}{E_2}\sigma_z \\ \varepsilon_z = \dfrac{\mu_2}{E_2}\left(\sigma_\theta + \sigma_r\right) + \dfrac{1}{E_2}\sigma_z \\ \gamma_{r\theta} = \dfrac{2\left(1+\mu_1\right)}{E_1}\tau_{r\theta} \\ \gamma_{\theta z} = \dfrac{1}{G_2}\tau_{\theta z} \\ \gamma_{zr} = \dfrac{1}{G_2}\tau_{zr} \end{cases} . \quad (5)$$

Based on the above analysis and assumptions, the composition of kitchen waste belongs to a composite material composed of multiple materials, and continuity conditions need to be used to describe the relationship between different components. Therefore, the boundary conditions are set as follows:

$$\begin{cases} \sigma_r = -p, r = \dfrac{1}{2}D, \theta = \dfrac{1}{2}\pi \\ \sigma_{ij} = 0, other \end{cases} . \quad (6)$$

After sorting, the strength conditions of kitchen waste are obtained, and as long as the strength of the waste is destroyed, the destruction of the waste can be achieved [16]. The strength conditions are as follows:

$$\begin{cases} H = \dfrac{1}{2}\left(\dfrac{1}{X^2} + \dfrac{1}{Y^2} - \dfrac{1}{Z^2}\right) \\ G = \dfrac{1}{2}\left(\dfrac{1}{X^2} - \dfrac{1}{Y^2} + \dfrac{1}{Z^2}\right) \\ F = \dfrac{1}{2}\left(-\dfrac{1}{X^2} + \dfrac{1}{Y^2} + \dfrac{1}{Z^2}\right) \\ L = \dfrac{1}{2S_{23}^2} \\ M = \dfrac{1}{2S_{31}^2} \\ N = \dfrac{1}{2S_{12}^2} \end{cases} . \quad (7)$$

The theoretical mechanical model of kitchen waste has been obtained above. In order to supplement the above theoretical model and add the maximum stress intensity criterion, orthogonal anisotropic materials have three mutually perpendicular planes. If the three mutually perpendicular main axes of the material are used as the main stress directions, as long as the stress component in any direction exceeds the maximum stress value of the material, it is considered that the material has been damaged. The tensile stress is expressed as:

$$\begin{cases} \sigma_r < X_t \\ \sigma_z < Y_t \\ \left|\tau_{12}\right| < S \end{cases} . \quad (8)$$

After supplementation, the geometric equations in cylindrical coordinates and the equilibrium equations in macroscopic elasticity were obtained, and the equilibrium equation represented by displacement was derived. The boundary conditions and continuity conditions for kitchen waste were also provided, which improved the differential equation. According to the commonly used strength criteria for three types of anisotropic materials, different from those for homogeneous materials, the strength conditions for anisotropic materials are considered to have been damaged as long as one inequality is not met, and this serves as the basis for the fracture mechanism.

4 Modeling and Simulation Analysis of the Crushing Mechanism

Taking into account the various crushing conditions mentioned above, it is necessary to consider various aspects such as the operating conditions of the crusher, the size of the entire machine, the characteristics of kitchen waste components, the approximate size of initial processed materials, the size of materials after treatment, and the requirements for processing capacity. The basic crushing conditions are set as shown in Table 1.

Table 1. Initial design parameters of crusher

Name	Design indicators
Garbage composition	Leftover vegetables, leftover rice, fruit peels, bones, grains, meat and eggs
Initial particle size	$\leq 100mm$
Particle size after crushing	$\leq 5mm$
Crushing capacity	$\geq 0.6t/h$
Tooth roller outer circle diameter	120mm
Axis roller length	300mm

According to the selection of relevant small double spoke mechanisms, the range of linear velocity values at the top of the gear teeth is roughly between 150mm/s and 800mm/s. Design the diameter of the toothed roller to 104mm, and according to equation 9, the speed range of the toothed roller crushing mechanism can be obtained [17]. Due to the complex composition of the processed material and the presence of hard bones, it is advisable to choose a lower rotational speed.

$$n = \frac{60v}{\pi D} = \frac{60 \cdot (150 - 800)}{\pi 120} = 23.9r/\min - 127.4r/\min . \tag{9}$$

In summary, considering the working conditions and crushing requirements of the kitchen waste crusher, the crusher speed in this article adopts $35r/\min$.

4.1 Three Model Structure Design

Based on the preliminary parameter settings, establish a three-dimensional model of the crusher, and the designed three-dimensional model of the kitchen waste structure is shown in Fig. 2.

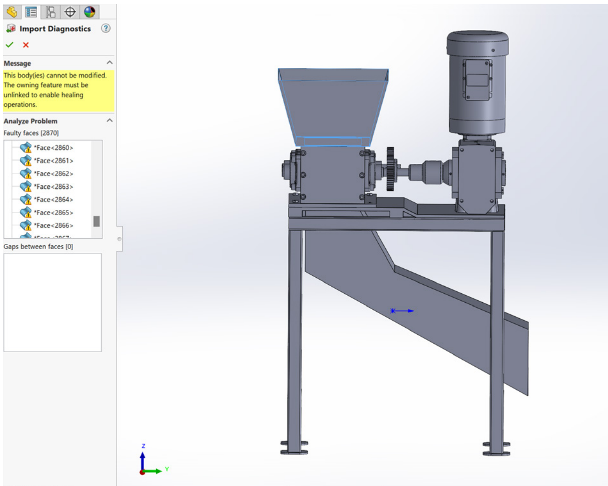


Fig. 2. 3D model of crusher

Due to the involvement of many related influencing factors in the design of tooth profile parameters, in order to highlight the main factors and design effects, the content of the studied tooth profile parameters has been simplified. Only the basic structural parameters that can describe the general shape of the eagle nose shaped crushing tooth, including tooth width b_1, tooth height h, crushing tooth thickness b_2, elevation angle α between the matrix and crushing teeth, number of teeth on one ring z, tooth tip fillet r_1, tooth tip transition fillet r_2, transition fillet r_3 between the matrix and tooth tip, transition fillet r_4 between the matrix and tooth back, and tooth back fillet r_5, are studied, as shown in Fig. 3.

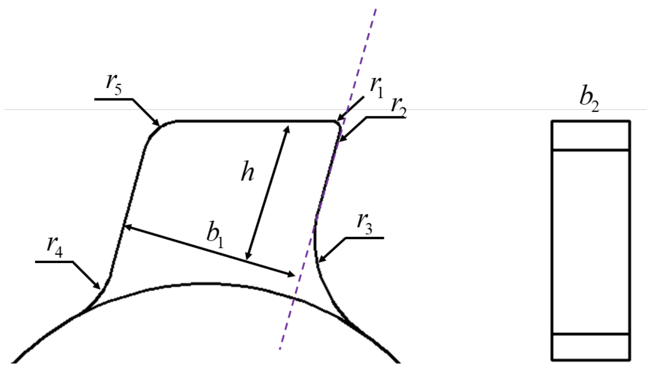


Fig. 3. Tooth structure parameters

The tooth height h is the radial distance between the crushing teeth and the substrate. To ensure that kitchen waste is more easily bitten by the crushing teeth, the tooth height value should not be too small, usually 1.5 times the product size; The tooth width b_1 is the size of the broken teeth in the circumferential direction of the matrix, which has a significant impact on the strength of the teeth. It is recommended to take a larger value, generally one time the tooth height. The fracture tooth thickness b_2 directly forms the axial size of the polygonal gap. To ensure the particle size of the fracture product, the tooth thickness b_2 is equal to the target size after garbage treatment. In summary, the values are shown in Table 2.

Table 2. Grinding teeth parameters

Parameter name	Design indicators
h	15mm
b_1	$1\times h=15mm$
b_2	6mm
α	72°
z	15
l	13mm

The spacing between the broken teeth is directly determined by the number of teeth z on the ring. When the spacing is large, the biting ability of kitchen waste also increases, but the particle size of the broken products also increases. According to the principle of probability screening, the number of teeth is determined by taking the circle that passes through the midpoint of the teeth.

The formula for determining the number of teeth is as follows:

$$z=\frac{\pi\left(D-h\right)}{b_1+l}. \tag{10}$$

l represents the tooth spacing value as shown in Table 2. According to formula 10, the number of rulers can be calculated as 11.7, and the selected ruler in this article is 12.

4.2 Roller Tooth Structure Design

The design of the toothed roller includes the following main parameters: radius r_7 of the transmission core shaft, pitch p between adjacent crushing toothed rings, radius r_8 of the spacer sleeve, thickness b_3 of the spacer sleeve, number of toothed rings n, helix angle β of the toothed ring, center distance a of the two toothed roller shafts, and mutual embedding depth m of the crushing teeth. The design of tooth roller parameters should first meet the expected particle size after kitchen waste treatment, secondly ensure good material biting ability, and finally consider reasonable force distribution on the tooth roller shaft. The roller tooth structure is shown in Fig. 4.

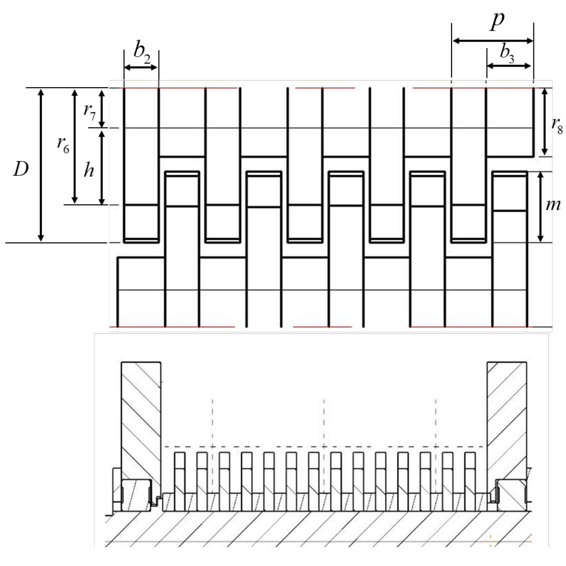


Fig. 4. Schematic diagram of roller tooth structure

When processing kitchen waste, it should be broken into finer particles. Therefore, the core shaft diameter is set to 0.3 times the major diameter of the roller tooth shaft, resulting in a core shaft diameter of 36 millimeters. At the same time, the operating length of the tooth roller is designed to be $L = 300mm$, which is 2.5 times the major diameter of the tooth roller, meeting the value range requirements. After the above design analysis, the design result shown in Fig. 5 is obtained.

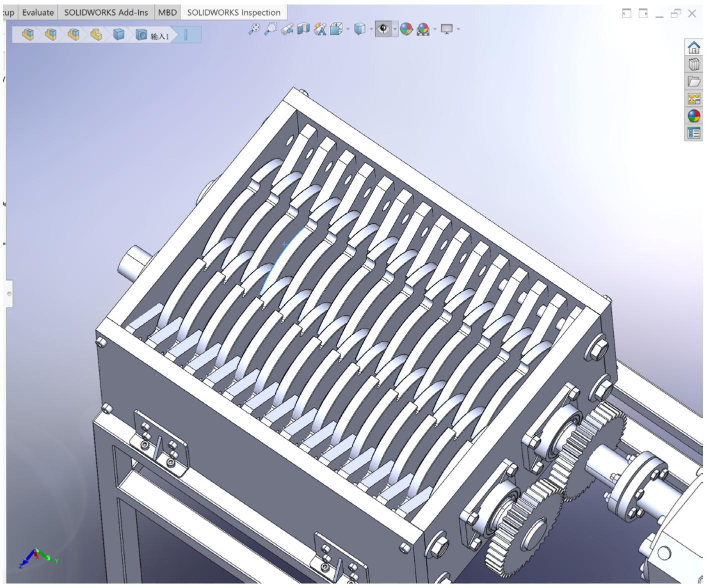
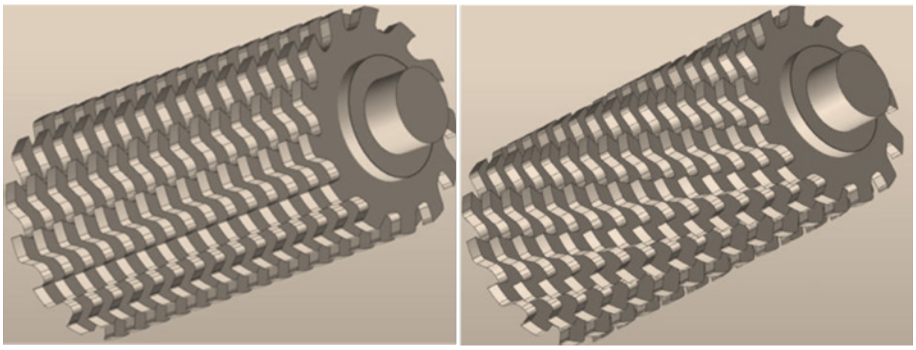


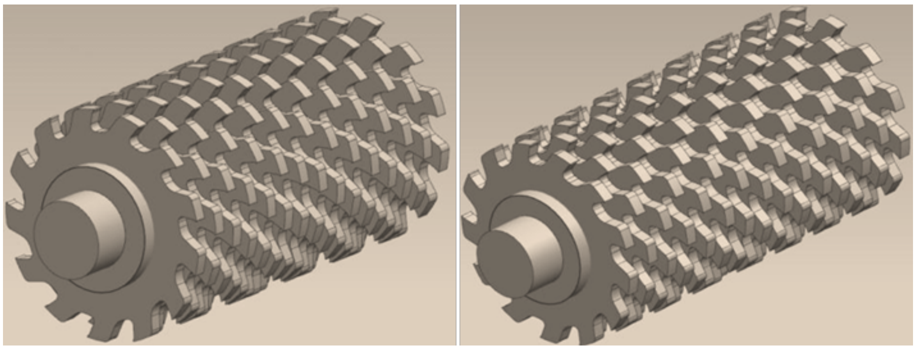
Fig. 5. Roller tooth structure

4.3 Establishment of Discrete Element Analysis Model

According to the mechanical research of kitchen waste crushing process, which belongs to multiphase mixed dispersion, the simulation CAE software EDEM is used to optimize the parameter simulation design of the crushing tooth shape structure and the staggered arrangement of tooth rings along the axis [18]. Import the design model into simulation software, and analyze the main objective of the impact of tooth ring interlocking angle on crushing performance, kitchen waste biting ability, unit time output, and year-on-year power consumption. Establish a geometric model for discrete element simulation of four scenarios: 0°, 7°, 13°, and 18° staggered angles between adjacent broken tooth rings. The model is shown in Fig. 6.



0° 7°



13°　　18°

Fig. 6. Structure of roller teeth at different angles

Place the garbage particle generation plane above the crushing toothed roller and leave enough space to replace the required step size for the foot particles. Particle generation plane type selection is virtual, and displacement is fully constrained. The total amount of particle generation depends on the situation, and the number of particles has little impact on the calculation process, but it will increase the total amount of result data.

Define the overall size of the garbage particles entering the crushing bin, and then fill them with smaller particles to form Bond bonds between the small particles. This process can be likened to filling a ball with fine sand. It should be noted that particle replacement requires building a shell model using SolidWorks modeling software, then constructing the number of small particle fills and the spatial location of each particle. The parameter code is saved in three files, and finally, small particle filling is performed in EDEM. Replace the call file and the spatial coordinates of each small particle. The particle model is shown in Fig. 7.

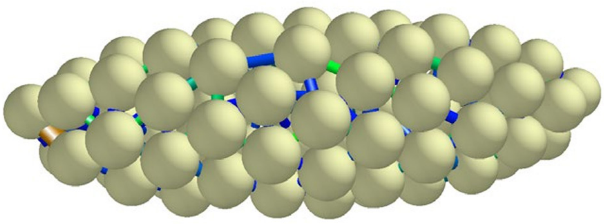


Fig. 7. Structure of roller teeth at different angles

This chapter mainly completes the creation of the model of the crusher, preparing for further crushing simulation experiments.

5 Simulation Experiments and Result Analysis

This section mainly analyzes the simulation and optimization results of the roller teeth and cross angle optimization of the kitchen waste crusher through simulation modeling. It analyzes the crushing performance under different angle settings, and then determines the crushing angle and cross angle to calculate the crushing capacity under the optimal structure, that is, the amount of kitchen waste crushing in a single position time.

5.1 Structural Optimization Simulation

Fig. 8 is a screenshot of the simulation process of kitchen waste crushing in a double toothed roller mechanism.

During the main crushing stage of 0.1s to 1s, comparing the slopes of the four curves, it can be concluded that the order of Bond fracture rates is 13° > 7° > 18° > 0° helix angle. The spiral interlocking angle of 13° can bite into the material faster than the other control groups for crushing, and the remaining number of Bond bonds it reaches is relatively lower, with more bond breakage. After 1.3 seconds, all four curves tend to stabilize and slowly decrease at an extremely low speed with some fluctuation, which is caused by the random and discontinuous fragmentation of residual materials. At the end point of 2.8 seconds after the simulation, it can be observed that the residual quantity after Bond bond fracture is ranked as 13° > 7° > 18° > 0° spiral staggered angle. Analysis of the result: During the simulation process, when garbage falls into the toothed rollers for crushing, the spiral interlocking angle between the toothed rings provides axial force to the material, causing it to move laterally along the axis and increase the crushing contact surface, thereby affecting the final key breaking and crushing effect. Therefore, a spiral angle of 13° is selected.

For the selection of gear interlocking angle, simulation methods are also used to verify the impact of interlocking angle on the crushing results.

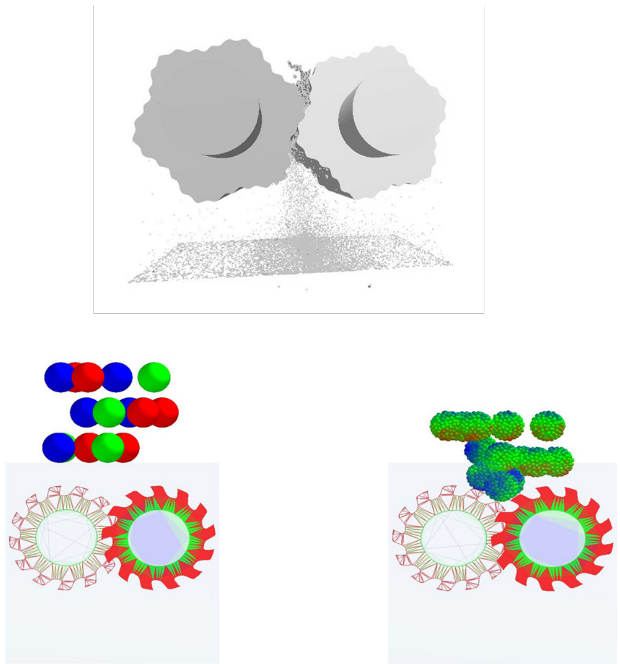


Fig. 8. Crushing simulation process

As shown in Fig. 9, the average power bar chart of four types of spiral angle toothed roller operations throughout the simulation process. The order of the required average power can be clearly obtained: 0° > 18° > 13° > 7°. It can be seen that the spiral interlocking angle between the broken tooth rings can reduce the required average power, and the required average power shows a trend of first decreasing and then increasing as the spiral angle increases. Analysis of the result: Appropriate small angle interleaving can effectively reduce the ineffective work of processing materials, but excessive interleaving angles can even exacerbate the collision, jumping, or rolling phenomenon of materials, and instead consume power. From the perspective of garbage production, the same 13° angle results in the highest garbage production. In summary, although 13° angle cannot guarantee the lowest power, other aspects of performance are optimal. Therefore, this article chooses the spiral angle of the teeth as 13°.

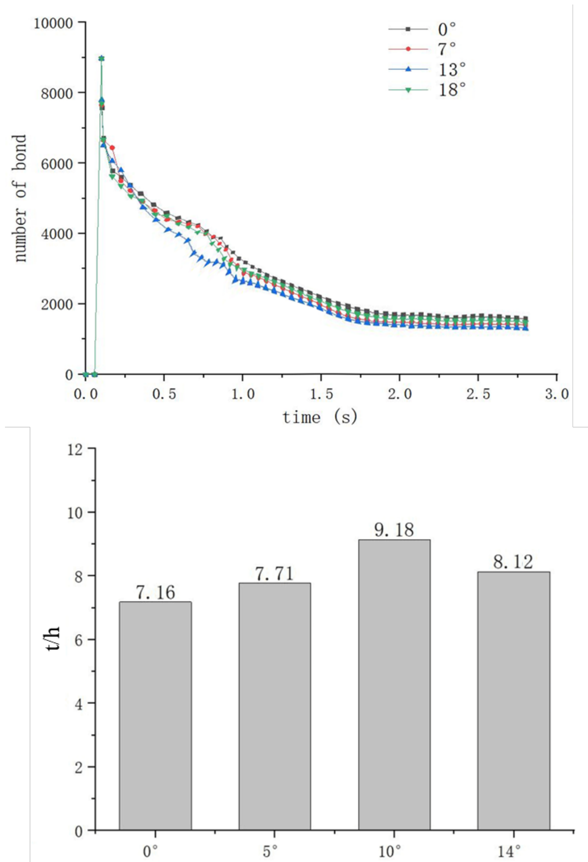


Fig. 9. Simulation of crushing effect

5.2 Simulation Analysis of Crushing Ability

Do not consider the situation where kitchen waste rolls or moves laterally on the double toothed roller during crushing, and ignore the very small amount of waste that falls from the gap between the toothed roller and the side baffle. Assuming the process of kitchen waste from falling into the crushing chamber to being crushed and discharged, the waste completely fills the crushing interval between the two toothed rollers and is forced to fall without adhesion, the production per unit time is only calculated from the geometric dimensions of the toothed roller crushing mechanism. Due to the fluffiness and numerous gaps in the interior of kitchen waste, materials will inevitably fall non continuously in the normal and axial directions during crushing. Therefore, the material filling coefficient is introduced to correct this situation. Looking up the filling coefficients of each component of kitchen waste, summing them up and taking the average, the material filling coefficient is 0.4.

The theoretical crushing capacity of kitchen waste should be: the total volume passing through the red working area per unit time minus the space passed by the crushing teeth. It should be noted that when calculating the former, the volume of the overlapping part of the broken teeth should be removed to avoid duplicate calculations. The formula for calculating the crushing amount is as follows:

$$V = \rho T\left(V_1 - V_2\right). \tag{11}$$

Among them, R represents the crushing yield of kitchen waste in units of B, C represents the density of kitchen waste in units of D, E is the filling coefficient, and F is the total volume passing through the crushing operation area; G is the total volume of broken teeth passing through.

In order to calculate the amount of crushing, it is necessary to correctly represent H and I, as follows:

$$V_1 = 30n\pi d\left(D^2 - 4r^2 + 2a^2 - 2aD\right). \quad (12)$$

$$V_2 = 60nmV_d. \quad (13)$$

In the formula, A represents the radius of the spacer, H represents the tooth height of the roller teeth, D represents the maximum diameter of the roller teeth, a represents the center distance between two rollers, n represents the roller speed, M represents the total number of crushing teeth, and V_d represents the volume of a single crushing tooth. Consider a single crushing tooth as a regular shaped cube for approximate calculation. After calculation, the amount of kitchen waste treatment $V = 1.47t / m^3$ was obtained, which meets the design requirements.

In summary, the optimization of the roller and roller tooth structure inside the crushing mechanism was completed in this stage, and the unit time crushing amount of garbage was calculated, verifying the crushing ability of the crushing mechanism designed in this article for kitchen waste.

6 Conclusion

The research object of this article is the garbage crushing device, with the aim of designing a more efficient and reasonable garbage crusher. The core structure of the garbage crusher is the garbage crushing roller tooth structure, and factors such as the tooth shape and angle of the roller teeth determine the crushing effect on kitchen waste. Therefore, this article first establishes a kitchen waste model and analyzes the crushing conditions of kitchen waste. Then, based on the garbage model, a roller tooth model of the crusher is established, and parameters such as the roller tooth shape and the cross angle of the roller teeth are optimized and analyzed to obtain the optimal parameters.

1) By analyzing the composition and generation methods of kitchen waste, an effective mathematical model that can reflect kitchen waste to the maximum extent possible and accurately is established, which facilitates the design and analysis of crushers.

2) A three-dimensional model of the garbage crusher was established, and finite element analysis was used to optimize the parameters of the three-dimensional model, in order to obtain the optimal parameters for each structure of the crusher.

3) Considering the urban waste treatment process, this equipment will be arranged in the community, where the concentrated kitchen waste will be collected and crushed before proceeding to the next step of treatment.

At the same time, there are also some research shortcomings in this article, and further in-depth research will be conducted in the future, which will also serve as the further research direction of this article. The summary is as follows:

1) Further optimize the overall structural dimensions of the crusher, and conduct research based on the application scenario of the crusher, i.e. community, the overall size of the crusher, the working noise of the crusher, and the mechanism of noise generation.

2) This article mainly studies the mechanism of the crusher itself. Combined with automation control, this article will further develop an automatic kitchen waste crushing device. At the same time, combined with the Internet of Things, the crushed kitchen waste will be connected in real-time with the recycling station to ensure the timely removal of community waste and minimize the pollution caused by garbage stacking to the community.

On the basis of summarizing the research results of this article, this article also makes corresponding prospects for the future treatment of kitchen waste from the perspectives of garbage treatment system and treatment technology.

1) At the technical level, during the exploration process of this project, although the optimization of various components in the simulation system was completed and ideal optimization results were obtained, there is a lack of support from modern Internet of Things technology. If comprehensive monitoring and status management of multiple kitchen waste crushing equipment are achieved, it can improve the efficiency of community management and enhance social happiness index. Due to the lack of real-time dynamic data between various components

and the connection between 3D models, as well as data analysis, the next step is to establish a digital simulation system for the entire equipment. The focus of the work should be as follows: using cloud computing and big data to analyze the historical operating data of each component, and using machine learning algorithms to analyze the possible losses and faults of the equipment; By utilizing digital twin technology, we aim to improve the equipment simulation system and conduct in-depth exploration of the entire lifecycle of crushing equipment from design, production, use, and maintenance.

2) At the institutional level, it is necessary for local governments to establish scientific waste disposal standards and encourage the promotion and use of kitchen waste disposal machines. The existing garbage disposal methods are too extensive, and while vigorously developing the garbage disposal industry, attention should be paid to the refinement of garbage disposal. The implementation of garbage classification system is a necessary condition for the scientific treatment of garbage in China. Garbage classification helps people change the old concept of discarding garbage, and is also conducive to the promotion of household kitchen waste disposal machines; At the same time, we need to promote from small areas to large areas and expand the market for kitchen waste crushing equipment. It can also be promoted from first and second tier cities to all urban communities. The promotion of community kitchen waste treatment equipment is not only the work of enterprises, but also requires government policy support. As an environmentally friendly product, it can also increase social awareness through education and publicity to the public. From the perspectives of policy, education, and business, the popularity of household kitchen waste disposal machines will be promoted by leaps and bounds.

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References

[1] G.-X. Qi, Z.-Y. Liu, Y. Xia, S.-H. Chen, J.-H. Hu, L.-H. Ren, The Impact of Physical Composition on the Composition and Emission Characteristics of Odorous Pollutants During Food Waste Composting, Environmental Sanitation Engineering 31(6)(2023) 54-62.

[2] C.-F. Ren, F.-F. Song, M.-J. Ruan, X.-W. Huang, C.-J. Fang, Development and Application on Mechanical-Biological Treatment Technology of Municipal Solid Waste, China Environmental Protection Industry (10)(2023) 48-52.

[3] Y.-L. Chen, Y. Wu, J. Shan, X.-X. Hu, D.-M. Sun, J.-F. Zhang, Progress of Gas Deodorization Technology in Food Waste Treatment Process, Environmental Engineering 41(S2)(2023) 475-478.

[4] G. Song, P. Zhang, W.-W. Lian, D.-J. Du, J.-F. Xiao, Performance Simulation Study of Rural Kitchen Waste Crusher with Double Toothed Rollers Based on Discrete Element Method, Agricultural Engineering 13(11)(2023) 93-97.

[5] S. Feng, Y.-G. Wang, X.-K, Wang, H. Yuan, W. Liu, P.-N. Guo, Study on performance of kitchen waste spiral extrusion device based on discrete element method, Food & Machinery 38(4)(2022) 109-113.

[6] J.-P. Chang, L. Guo, X.-M. He, J.-K. Wang, Q.-M. Fang, Optimization and test study on parameters of helical axis based on EDEM solid-liquid separation device, Food & Machinery 38(7)(2022) 128-132.

[7] Y.-H. Xu, F. Xu, Z.-K. Zhao, H.-K. Yang, The Design of a Community Kitchen Waste Classification and Recycling Device, Henan Science and Technology 41(13)(2022) 32-35.

[8] X. Fu, D.-J. Guo, H. Chen, H. Zhang, H. Yu, Y.-F. Yang, Y.-M. Li, Design of Multistage Crushing and Forming Machine for Domestic Waste, Mechanical & Electrical Engineering Technology 51(11)(2022) 73-75.

[9] B. Zhu, Kitchen Waste Crusher with Different Cutter Teeth Structure, Agricultural Equipment & Vehicle Engineering 60(1)(2022) 107-110.

[10] G.-H. Lin, L.-K. Xu, X.-Y. Liu, Research and Design on Kitchen Waste Disposal Device of Large Cruise Ship, Ship Engineering 42(S1)(2020) 302-306.

[11] Y.-B. Hu, S.-F. Wang, W.-C. Xiao, Design of mechanical compressive treatment device for wet waste, Chinese Journal of Engineering Design 28(3)(2021) 374-380.

[12] Z. Chu, N.-C. Ding, Z.-J. Huan, Y.-W. Tian, J. Zhou, Review of Domestic Kitchen Waste and Food Residue Treatment Technology, Guangdong Chemical Industry 50(22)(2023) 103-105+150.

[13] W.-M. Deng, Research Progress on Characteristics and Fuel Treatment Technology of Food Waste, Guangdong Chemical Industry 48(23)(2021) 137-141+130.

[14] K. Zhang, S, Zhang, W.-D. Yu, D.-F. Zou, Numerical Simulation Analysis of Screw Based on Discrete Element-Finite Element Coupling Simulation, Journal of Shenyang Jianzhu University (Natural Science) 37(4)(2021) 746-752.

[15] Z.-H. Wu, Y. Li, C.-F. Guo, N.-B. He, D.-Y. Yao, S.-Q. Wei, Design and simulation analysis of self-propelled banana straw crushing and returning machine, Journal of Chinese Agricultural Mechanization 43(9)(2022) 40-46.
[16] H.-M. Dong, S.-K. Wen, Y. Wang, Finite Element Analysis of PCM400 Type Hammer Crusher Based on ABAQUS, Coal Technology 35(7)(2016) 264-266.
[17] J.-K. Shui, K. Liao, T.-Y. Yang, L.-J. Li, Z.-C. Gao, L.-N. Song, Design and Experimental Study on Key Components of Wood Pile Crusher, Journal of Mechanical Strength 43(6)(2021) 1402-1408
[18] L.-H. Jia, Y.-Q. Xiao, C. Zhao, Y.-Z. Cai, W.-W. Zhang, J. Chen, Study on mud-water shield circulation system's slurry slag-carrying characteristics based on CFD-DEM method, Journal of Machine Design 40(12)(2023) 126-132.