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Research on new process for separation of silicon wafers and glass from decommissioned photovoltaic modules

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Abstract: In view of the disadvantages of the existing electrostatic separation process of decommissioned photovoltaic modules, which can only achieve the separation of fine silicon wafers and glass and has high energy consumption, a new process to solve the efficient dry separation of coarse silicon wafers and glass in decommissioned photovoltaic modules is proposed- the vibration separation method. Based on the theoretical analysis of the vibration separation of flaky silicon wafer and polyhedral glass particles, the effects of feed size, feed amount, vibration voltage, vibration frequency, horizontal inclination angle and longitudinal inclination angle on the product indexes of wafer and glass separation were investigated by single factor experiment. The optimal experimental conditions were obtained as follows: feed particle size +0.83mm, feed amount 0.15 t/h, vibration voltage 190 V, vibration frequency 48 Hz, horizontal inclination Angle 8°, longitudinal inclination Angle 3°. Under this optimized condition, the content of metal Si in the obtained silicon wafer product is 84.47%, the recovery rate of is 83.73%, the content of impurity SiO_2 is 1.09%, and the content of SiO_2 in the obtained glass product is 65.69%, and the recovery rate is 98.95%, the impurity metal Si content is 0.56%. This study provides a research idea for the industrial separation of silicon wafers and glass from decommissioned photovoltaic modules.

Keywords: crystalline silicon photovoltaic modules, decommissioned photovoltaic modules, silicon solar cell, tempered glass, vibration separation

1. Introduction

More than 130 countries and regions in the world, including China, the European Union, the United States and Japan, have successively put forward the goal of "carbon neutrality" one after another. The global energy transformation and upgrading is the general trend, and the scale of photovoltaic (PV) power generation will continue to accelerate expansion. Under the background of the implementation of China's "dual carbon" strategic goal, the photovoltaic power market has entered a stage of explosive growth. Starting from 2025, the global decommissioned PV modules will enter a stage of explosion. It is estimated that the world's cumulative amount of decommissioned PV modules in 2030 will be about 8 million tons, with a market size of about 38 billion yuan. In 2050, the world's cumulative amount of decommissioned PV modules will be about 78 million. tons, with a market size of about 370 billion yuan (Heath et. al., 2020). It is estimated that the cumulative decommissioning of PV modules in China will be about 1.5 million tons by 2030, with a market size of about 7 billion yuan. In 2050, the cumulative decommissioning of PV modules in China will reach 20 million tons, with a market size of about 95 billion yuan (Mahmoudi et. al., 2021). The market for the disposal and recycling of decommissioned PV modules is promising. From 2021, various departments in China have begun to pay attention to the recycling of decommissioned PV modules. Since 2021, China has successively issued the "14th Five-Year Plan for Circular Economy Development", the "Carbon Peak Action Plan before 2030", the " Action Plan for Innovative Development of Intelligent PV Industry (2021-2025), and the Implementation Plan for

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Accelerating the Promotion of Comprehensive Utilization of Industrial Resources, propose to promote the R&D and industrial application of emerging solid waste comprehensive utilization technologies such as decommissioned PV modules, and increase the comprehensive utilization of complete sets of technical equipment research and development efforts.

Decommissioned PV modules contain valuable metals such as copper, aluminium, silicon, and silver, which have considerable recycling value (Zhou et. al., 2020). Through centralized disposal of decommissioned PV modules, the recycling of valuable components such as aluminum frame, silicon cells, tempered glass, metallic silver and tin coated tape of PV modules can be realized, which is of great significance in terms of resource recovery, environmental protection and employment increase (Lunardi et. al., 2018; Dias et. al., 2021). Silicon cells (referred to as silicon wafers) and tempered glass (referred to as glass) are the main components in the recovery of decommissioned PV modules. These two components account for about 3.65% and 70.00% of the weight of the PV modules (Zhou et. al., 2020), respectively, and these two components account for about 56.66% and 5.78% of the value of PV modules (Zhang et. al., 2022), respectively. At present, electrostatic separation method (Dias et. al., 2018; Yang et. al., 2019) is one of the physical separation methods to effectively separate silicon wafers and glass in decommissioned PV modules, However, the electrostatic separation method could only realize the separation of fine-grained silicon wafers and glass. Since the electrostatic separation method requires the moisture content of the selected materials to be less than 0.5%, it must be dried treatment before electrostatic separation to remove moisture and restore the intrinsic conductivity of silicon wafers and glass particles, and there is a problem of high energy consumption. In view of the separation problem of coarse-grained flaky silicon wafers and polyhedral glass particles, based on the theoretical analysis of the vibration separation process, this paper proposes a new process to solve the efficient dry separation of coarse silicon wafers and glass - the vibration separation method, in order to provide theoretical basis and solutions for the separation of silicon wafers and glass from decommissioned PV modules.

2. Materials and methods

2.1. Experimental material

The raw material of this experiment was the silicon wafer glass mixture larger than 0.83mm obtained after the heat treatment (Dias et. al., 2017; Wang et. al., 2019; Fiandra et. al., 2019) that EVA was completely decomposed and sieved (Pagnanelli et. al., 2019) from the decommissioned monocrystalline silicon or polycrystalline silicon PV modules with the back sheet removed, and the comprehensive study of the raw material through microscopic identification, X-ray diffraction analysis and scanning electron microscopy analysis showed (Hamdani et. al., 2019; Anada et. al., 2020) that the raw material was relatively simple and the main components were silicon wafers and glass. The results of X-ray fluorescence spectrum analysis, main chemical composition analysis, and X-ray diffraction analysis of raw materials are showed in Table 1, Table 2 and Fig.1, respectively.

Table 1. Semi-quantitative analysis of raw materials by XRF spectrum (mass fraction, %)

Elements	Si	O	Na	Ca	Al	Mg	Sb	S	Fe	Cu
Content	37.23	40.00	9.30	6.09	5.214	1.70	0.142	0.114	0.053	0.045
Elements	Cl	K	Ag	Pb	P	Ti	Cr	Zr	Ni	Zn
Content	0.038	0.035	0.017	0.011	0.01	0.01	0.009	0.005	0.004	0.004

Table 2. Analysis of main chemical constituents of raw materials (mass fraction, %)

Constituents	Si	SiO_2	Na_2O	MgO	Al_2O_3	CaO	Fe_2O_3	Ag*
Contents	8.58	59.86	10.94	2.95	7.90	7.76	0.069	851.10

Note: "*" unit was g/t

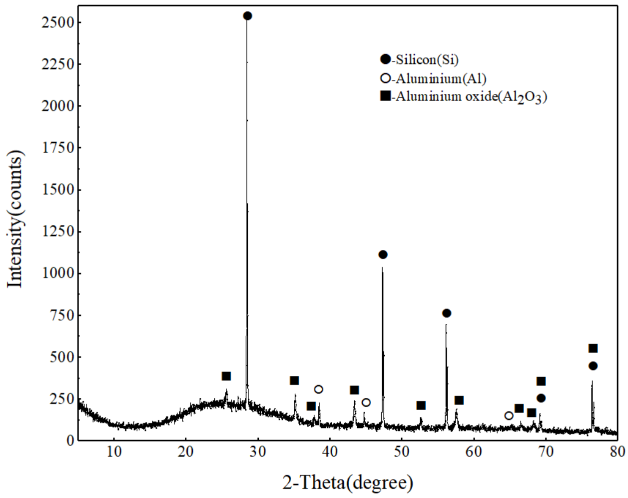

Fig.1. X-ray diffraction analysis of +0.83 mm silicon wafer glass mixture raw materials

It could be seen from Table 1 that the main elements in the raw materials were Si, O, Na, Ca, Al and Mg. It could be seen from Table 2 that the recyclable components in the raw materials were mainly metal Si, Al_2O_3, SiO_2, Na_2O, CaO, MgO and Ag, and the glass components SiO_2, Na_2O, CaO and MgO in the raw materials together account for more than 80%. Fig. 1 showed that there were X-ray diffraction peaks of metals Si, Al and Al_2O_3 in the silicon wafer. Because the glass was an amorphous substance, there were no obvious diffraction peaks of SiO_2, Na_2O, CaO and MgO, and only the steamed bread peaks in the amorphous state of the glass were displayed.

2.2. Experimental equipment and methods

The experimental equipment for the separation of silicon wafers and glass adopts the industrial vibration separation equipment with a power of 3kW independently developed by Changsha Research Institute of Mining and Metallurgy, as shown in Fig. 2.

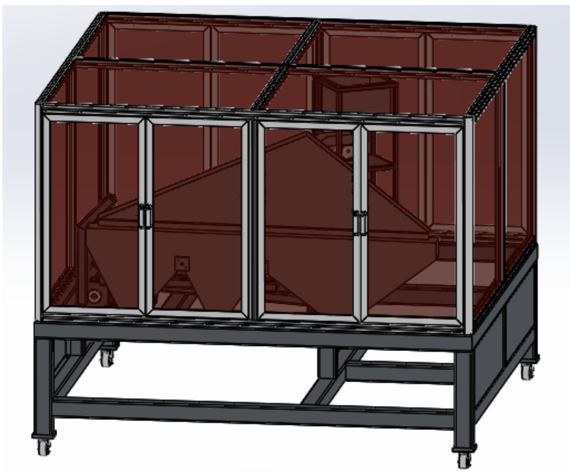

Fig. 2. Experimental equipment for vibration separation

Experimental method: the vibration voltage and vibration frequency of the vibration mechanism of the vibration separation equipment, the horizontal inclination angle and longitudinal inclination angle of the separation platform and other equipment parameters are adjusted in advance during the experiment. 1kg of pre-prepared representative silicon glass mixture is selected for each condition experiment. It is evenly fed into the vibration separation equipment separation platform from the feeding end. The silicon wafer products and glass products obtained by the vibration separation method are respectively weighing, sampling, grinding and sending analysis. The chemical phase analysis method is used to detect the content of metal silicon and silica phase in each product, and the recovery rates of metal silicon in silicon wafer products and silicon dioxide in glass products are calculated respectively. The calculation formula of recovery rate is as follows:

$$E = \frac{\gamma\beta}{\alpha} \times 100\% \tag{1}$$

In the formula: E is the recovery rate of useful components of the product, %; γ is the product yield, which refers to the percentage of product weight to raw material weight, %; β is the content of useful components of the product, %; α is the content of useful components of the raw material, %.

3. Results and discussion

3.1. Theoretical analysis of the vibration separation process of silicon wafer and glass

From the perspective of dynamics, during the vibration separation process of silicon wafer and glass mixed particles, due to the shape of silicon wafer and glass, friction coefficient and other physical properties, there are differences in the force and movement trajectory. Although the density of silicon wafers is close to that of glass, the density of silicon wafers is 2.35g /cm^3 and the density of glass is 2.50g /cm^3.When the silicon wafer glass mixture enters the vibration separation equipment for sorting, the material will be affected by gravity (Li et. al., 2019), frictional force (Yuan et. al., 2021) and inertial force (Agarwal et. al., 2021; Zhang et. al., 2021) during the separation process of the inclined sorting platform, the schematic diagram of the force analysis is shown in Fig. 3.

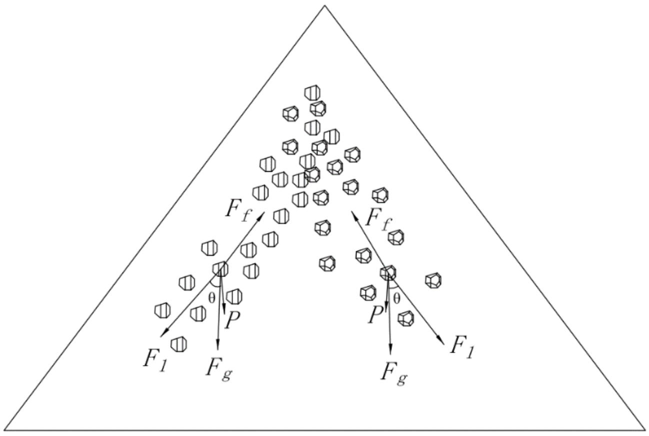

Fig. 3. Schematic diagram of force analysis during vibration separation process

The silicon wafer and glass mixture particles enter the vibration separation process, and the gravity on the separation platform is as follows:

$$F_g = mg \tag{2}$$

In the formula: Fg is the gravity of the particle, N; m is the weight of the particle, kg; g is the acceleration of gravity, N/kg.

The gravity of particles in the separation process can be divided into two parts: downward force along the inclined plane and perpendicular force to the inclined plane.

The silicon wafer and glass mixture particles will be affected by friction during the vibration separation process. Friction is mainly a force that is exerted by a solid when it is in contact with another solid contact surface when it is in relative motion, and its force direction is tangential to the contact surface. Friction can be said to be a binding force, and its essence is to limit the relative motion of objects. The size of the friction force is independent of the contact area, the friction coefficient is independent of the sliding speed, the static friction coefficient is greater than the sliding friction coefficient, and the friction force is proportional to the normal force:

$$F_f = P\mu \tag{3}$$

where F_f is the friction force, N; P is the normal force, N; μ is the friction coefficient.

The movement direction of the particles is determined by the direction of the inertial force, which is essentially the specific embodiment of the acceleration of the resultant force on the silicon wafer or glass particles (Wang, 2010). This force can be expressed by the following formula:

$$F_1 = \rho V \frac{dv}{dt} \tag{4}$$

In the formula: F_1 is the inertial force, N; ρ is the density of the particle, kg/m^3; V is the volume of the particle, m^3; v is the moving speed of the particle, m/s; t is the time, s.

In the process of vibration separation, the silicon wafer and glass particles follow Newton's laws of motion, and the three forces of gravity, friction and inertia force are superimposed on the particles to obtain the general form differential equation of the motion for silicon wafer and glass particles:

$$F_1 = m\frac{dv}{dt} = F_f + F_g \tag{5}$$

Substitute into the formula to get:

$$\frac{dv}{dt} = \frac{P\mu + mg}{\rho V} \tag{6}$$

During the vibration separation process of the silicon wafer and glass mixed particles, the friction force on the silicon wafer particles is greater than the downward component force of gravity along the inclined platform, that is, $F_f \geq F_{gp}$, $mg\sin\theta\mu \geq mg\cos\theta$, and the friction coefficient $\mu \geq \cos\theta/\sin\theta$, where θ is the angle between the gravity direction and the parallel inclination of the platform.

For glass particles, the frictional force received is less than the downward component force of gravity along the inclined platform, namely, $F_f \leq F_{gp}$, $mg\sin\theta\mu \leq mg\cos\theta$, and the friction coefficient $\mu \leq \cos\theta/\sin\theta$ at this time.

3.2. Effect of process parameters on the separation behavior of silicon wafer and glass

3.2.1. Effect of feed size on the separation behavior of silicon wafer and glass

The factors affecting the separation behavior of silicon wafer and glass include feed size, feed amount, vibration voltage, vibration frequency, horizontal inclination angle and longitudinal inclination angle, etc. The single factor experiment method was used to investigate the influence of these factors on the indexes of silicon wafer and glass separation products. the gravity and friction of silicon wafers and glass particles is directly affected by feed size. Feed size is one of the important technological factors affecting the vibration separation process. Too coarse or too fine particle size is not conducive to the vibration separation of silicon wafers and glass. If the material particle size is too coarse, the fluidity of glass particles is deteriorated, which is not conducive to the separation of silicon wafers and glass. The separation of the material is too fine, and the materials bounce frequently between the silicon wafer and the glass during the separation process, which will be mixed with each other, which is also not conducive to the separation of the silicon wafer and the glass. In this experiment, the fixed vibration separation equipment was feed amount 0.12 t/h, vibration voltage 180 V, vibration frequency 50 Hz, horizontal inclination angle of the platform 7°, longitudinal inclination angle of the platform 3°, and the feed size was a variable. The effect of feed size on the separation behavior of silicon wafer and glass was investigated, and the experimental results are shown in Fig. 4.

It can be seen from Fig. 4 that the vibration separation process has strong adaptability to the silicon wafer glass mixture of different feed particle sizes, that is, it can be selected from full-scale materials or classified materials, and both can obtain better quality experimental indicators. By changing the feed size, the metal Si content of the obtained silicon wafer product range from 83.30% to 84.03%, and the recovery rate is 82.01% to 83.48%. The SiO_2 content of glass product is 65.42%~65.71% and the recovery rate is 96.37%~96.90%. In order to simplify the technological process, after comprehensive investigation, the feed size +0.83mm full particle size is selected for subsequent experiments.

3.2.2. Effect of feed amount on the separation behavior of silicon wafer and glass

The feed amount is one of the important process factors affecting the vibration separation process. To obtain a better separation index of silicon wafers and glass, it is necessary to have a suitable feed amount. If the feed amount is too large，the separation accuracy is sharply reduced, which is not conducive to the vibration separation of silicon wafers and glass. If the feed amount is too small, the output and separation efficiency of the vibration separation system will be reduced, and the energy consumption cost will be increased. In this section, under the conditions of fixed feed size +0.83 mm, vibration voltage 180 V, vibration frequency 50 Hz, platform horizontal inclination angle of 7°, and longitudinal inclination angle of 3°, the feed amount was a variable, and the effect of feed amount on the separation behavior of silicon wafer and glass was investigated. The experimental results are shown in Fig. 5.

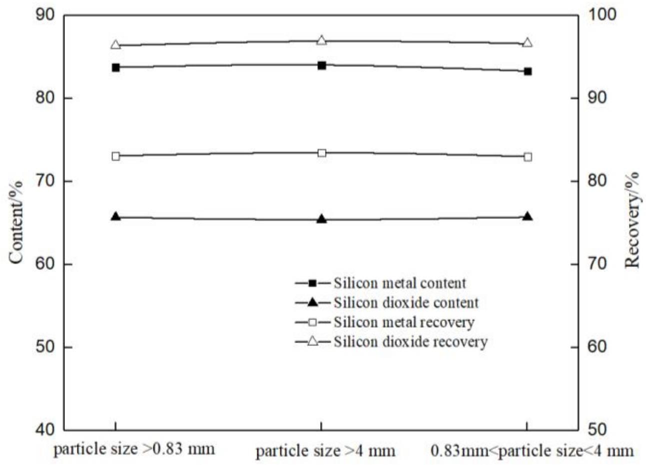

Fig. 4. Effect of feed size on the separation behavior of silicon wafer and glass

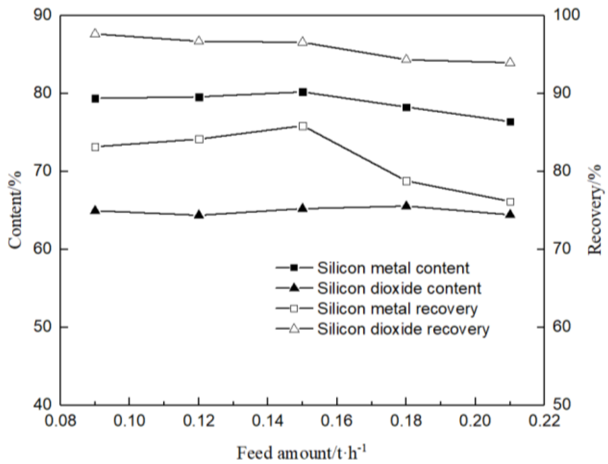

Fig. 5. Effect of feed amount on the separation behavior of silicon wafers from glass

It can be seen from the experimental results in Fig. 5 that when the feed amount is less than 0.15 t/h, the separation of silicon wafers and glass is promoted with the increase of the feed amount; when the feed amount is greater than 0.15t/h, the separation behavior of silicon wafers and glass is adversely affected with the increase of the feed amount. Specifically, with the increase of feed amount from 0.09 t/h to 0.21 t/h, the metal Si content and recovery rate of silicon wafer products are gradually increased first and then gradually decreased, while the SiO_2 content of glass product is gradually increased first and then decreased, and the recovery rate is gradually decreased. Comparing the quality indicators of silicon wafer products and glass products comprehensively, the experimental result is ideal when the feed amount is 0.15 t/h, and the separation effect of silicon wafer and glass is the best at this time.

3.3. Effect of equipment parameters on the separation behavior of silicon wafers and glass

3.3.1. Effect of vibration voltage on the separation behavior of silicon wafer and glass

Vibration voltage is an important factor that directly affects the separation behavior of silicon wafer and glass. The vibration force on silicon wafers and glass particles is related to the vibration voltage. The higher the vibration voltage, the greater the vibration force on the particles, which is more conducive to the separation of silicon wafers and glass particles. However, it cannot be generally considered that the higher the vibration voltage is, the better, because the vibration voltage required for each specific particle is different. When the vibration voltage is too low, the particle vibration force is insufficient, and it is impossible or difficult to effectively separate; when the vibration voltage is too high, the particle separation process bounces obviously, which will reduce the product quality index data of silicon wafers and glass products. In this section, under the conditions of fixed feeding particle size +0.83 mm, feed amount 0.15 t/h, vibration frequency 50 Hz, platform horizontal inclination angle of 7°, and longitudinal inclination angle of 3°, vibration voltage was a variable, and the effect of vibration voltage on the separation behavior of silicon wafer and glass was investigated. the experimental results are shown in Fig. 6.

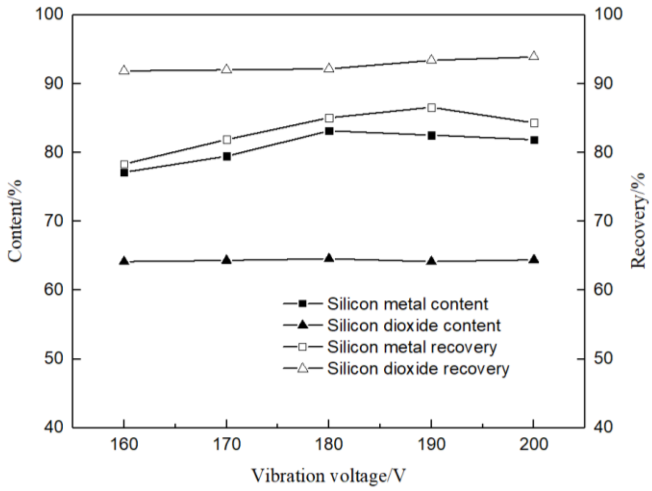

Fig. 6. Effect of vibration voltage on the separation behavior of silicon wafer and glass

The results in Fig. 6 show that when the vibration voltage is less than 190 V, as the vibration voltage increases, it promotes the separation behaviours of silicon wafer and glass, which is reflected in the metal Si content of silicon wafer products and glass products obtained by separation of silicon wafer and glass. The content of SiO_2 is gradually increased and then remained basically stable, and the recovery rate of metal Si in silicon wafer products and SiO_2 in glass products are increased gradually. When the vibration voltage is greater than 190V, as the vibration voltage increases, the adverse effect on the separation behavior of the silicon wafer and the glass gradually becomes prominent, which is reflected in the significant decrease in the metal Si content and recovery rate of the silicon wafer product obtained by separating the silicon wafer from the glass. The increasing trend of SiO_2 content and recovery rate of glass products are not obvious. Comparing the quality indicators of silicon wafer products and glass products comprehensively, the experimental results are ideal under the condition of vibration voltage of 190 V, and the separation effect of silicon wafers and glass is the best at this time.

3.3.2. Effect of vibration frequency on the separation behavior of silicon wafer and glass

The vibration frequency is also an important factor affecting the separation behavior of the silicon wafer from the glass. In a certain range, the higher the vibration frequency, the more conducive to the separation of silicon wafers and glass particles. If the vibration frequency is too high or too low, it is not conducive to the vibration separation of silicon wafers and glass. If the vibration frequency is too high, the number of bounces in the particle separation process will be too high, which will affect the product quality indicators of silicon wafers and glass products. If the vibration frequency is too low, the number of vibrations is not enough, and it is difficult to achieve the purpose of effective separation. In this section, under the conditions of fixed feeding particle size +0.83 mm, feed volume 0.15 t/h, vibration voltage 190 V, platform horizontal inclination angle of 7°, and longitudinal inclination angle of 3°, the vibration frequency was a variable, and the effect of vibration frequency on the separation behavior of silicon wafer and glass was investigated. The experimental results are shown in Fig. 7.

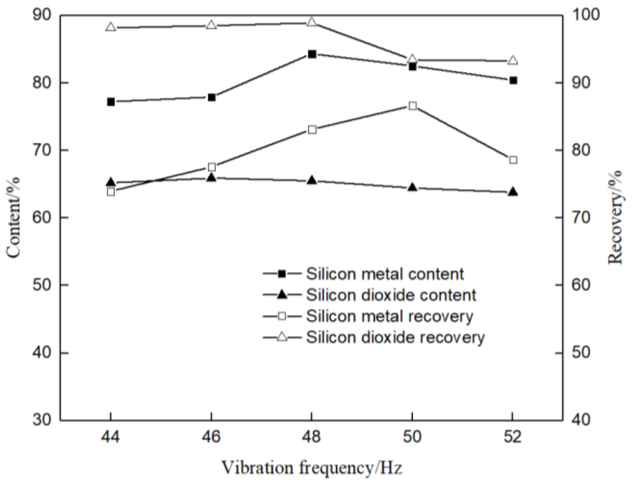

Fig. 7. Effect of vibration frequency on the separation behavior of silicon wafer and glass

The experimental results in Fig. 7 show that when the vibration frequency is less than 48 Hz, as the vibration frequency increases, the effect on the separation behavior of silicon wafer and glass is promoted, the metal Si content, metal Si recovery rate of silicon wafer and the recovery rate of SiO_2 in glass products obtained by the vibration separation of silicon wafer and glass are gradually increased. while SiO_2 content of glass has little change. When the vibration frequency is greater than 48 Hz, as the vibration frequency increases, it will have an adverse effect on the separation behavior of silicon wafer and glass， which is manifested as the metal Si content of silicon wafer products, SiO_2 content and SiO_2 recovery rate of glass products obtained from the vibration separation are decreased obviously, while the metal Si recovery rate increases first and then decreases. Comprehensively comparing the quality indicators of silicon wafer products and glass products, the experimental result is ideal when the vibration frequency is 48 Hz, and the separation effect of silicon wafer and glass is the best at this time.

3.3.3. Effect of horizontal inclination angle on the separation behavior of silicon wafers from glass

The inclination angle of the separation platform is divided into horizontal inclination angle and longitudinal inclination angle. The magnitude of the horizontal inclination angle and longitudinal inclination angle affects the magnitude and direction of the friction force between the silicon wafers and the glass particles, which in turn affects the resultant force of gravity, friction and inertial force on the separation platform and direction. The smaller the horizontal inclination angle is, the greater the friction force the particles are subjected to, which is beneficial to the vibration separation of silicon wafers, but is unfavorable to the vibration separation of polyhedral glass. The larger the horizontal inclination Angle is, the smaller the friction force is, which is beneficial to the vibration separation of polyhedral glass, but disadvantageous to the vibration separation of silicon wafer. In this section, under the conditions of fixed feed particle size +0.83 mm, feed amount 0.15 t/h, vibration voltage 190 V, vibration frequency 48 Hz, and platform longitudinal inclination angle of 3°, the horizontal inclination angle was a variable, and the effect of the horizontal inclination angle on the separation behavior of silicon wafer and glass was investigated. The experimental results are shown in Fig. 8.

It can be seen from the experimental results in Fig. 8 that when the horizontal inclination angle is less than 8°, as the horizontal inclination angle increases, it has a positive impact on the separation behavior of silicon wafer and glass, which is manifested as the metal Si content， metal Si recovery rate of silicon wafer products and the SiO_2 recovery rate of glass products obtained by the vibration separation of silicon wafer and glass are increased gradually, but the SiO_2 content of glass products has little change. When the horizontal inclination angle is greater than 8°, as horizontal inclination angle increases, it has an adverse effect on the separation behavior of silicon wafer and glass, which is manifested as the metal Si content, metal Si recovery rate of silicon wafer products and SiO_2 recovery rate of glass products obtained by the vibration separation of silicon wafer and glass products decreased significantly. Comparing the quality indicators of silicon wafer products and glass products comprehensively, it is ideal to choose the condition of horizontal inclination angle of 8°, and the separation effect of silicon wafer and glass is the best at this time.

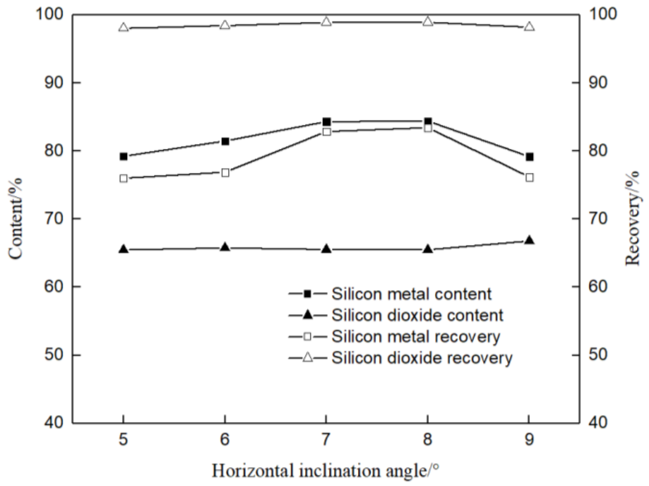

Fig. 8. Effect of horizontal inclination angle on the separation behavior of silicon wafers from glass

3.3.4. Effect of longitudinal inclination angle on the separation behavior of silicon wafers from glass

The size of the longitudinal inclination angle also directly affects the size and direction of the combined force of the respective gravity, friction and inertia force of the silicon wafer and the glass particles on the separation platform. The smaller the longitudinal inclination angle is, the greater the friction force is, which is beneficial to the vibration separation of silicon wafers, but is unfavorable to the vibration separation of polyhedral glass particles. The larger the longitudinal inclination angle is, the smaller the friction force is, which is favorable for the separation of polyhedral glass particles, but is not favorable for the vibration separation of silicon wafers. In this section, under the conditions of fixed feed particle size +0.83 mm, feed amount 0.15 t/h, vibration voltage 190 V, vibration frequency 48 Hz, and platform horizontal inclination angle of 8°, the longitudinal inclination angle was a variable, and the longitudinal inclination angle was investigated for the separation behavior of silicon wafer and glass. The experimental results are shown in Fig. 9.

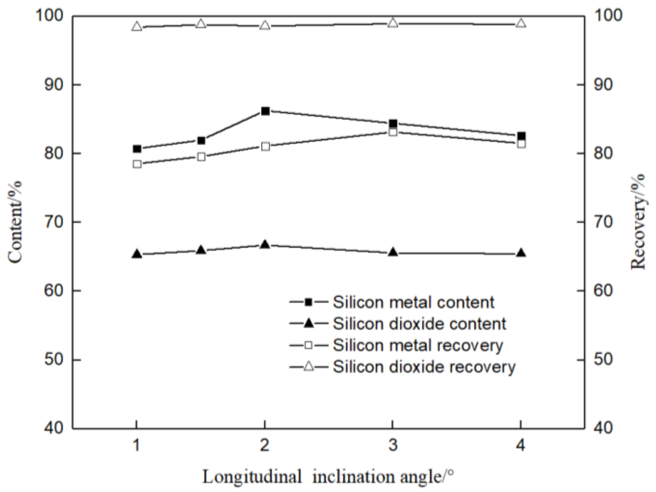

Fig. 9. Effect of longitudinal inclination angle on the separation behavior of silicon wafers from glass

From the experimental results in Fig. 9, it is found that when the longitudinal inclination angle is less than 3°, as the longitudinal inclination angle increases, it promotes the separation behavior of silicon wafer and glass, which is manifested as the metal Si content of silicon wafer products and the SiO_2 content of glass products obtained by the vibration separation of silicon wafer and glass gradually increased first and then decreased, while the recovery rate of SiO_2 in glass products has little change.

When the longitudinal inclination angle is greater than 3°, as the longitudinal inclination angle increases, it has an adverse effect on the separation behavior of silicon wafer and glass, which is manifested as the metal Si content and recovery rate of silicon wafer products from the vibration separation, while the SiO_2 content and recovery rate in glass products have little change. Comparing the quality indicators of silicon wafer products and glass products comprehensively, the experimental result is ideal when the longitudinal inclination angle is 3°, and the separation effect of silicon wafer and glass is the best at this time.

3.4. Optimal condition experiment

By using the single factor experiment method to investigate the effect of process parameters and equipment parameters on the vibration separation behavior of silicon wafer and glass, the optimal experimental conditions were obtained as follows: feed particle size +83mm, feed amount 0.15t/h, vibration voltage 190V, vibration frequency 48Hz, the horizontal inclination of the platform of 8°, and the longitudinal inclination of 3°. Under this optimized condition, the experimental results are shown in Table 3.

Table 3. Experimental results of optimal conditions (mass fraction, %)

product name	yield	content		recovery	
		metal Si	SiO_2 in glass	metal Si	SiO_2 in glass
silicon wafer	8.86	84.47	1.09	83.73	0.16
middle material	1.89	50.42	27.75	10.68	0.89
glass	89.24	0.56	65.69	5.59	98.95
mixed raw materials	100.00	8.94	59.25	100.00	100.00

The experimental results in Table 3 show that under the optimal experimental conditions, a silicon wafer product with a yield of 8.86%, a metal Si content of 84.47% in the silicon wafer, and a metal Si recovery rate of 83.73% can be obtained, The silicate SiO_2 content from the impurity glass in the silicon wafer is 1.09%, the yield of the obtained glass product is 89.24%, and the glass product with silicate SiO_2 content of 65.69% and SiO_2 recovery rate of 98.95% can be obtained, and the metal Si content of the impurity silicon wafer in the glass is 0.56%, the yield rate of the obtained silicon wafer glass intermediate product is 1.89%, and the intermediate product can be returned to the vibration separation process for re-separation of silicon wafer and glass.

4. Conclusions

1. The main elements of silicon wafer glass mixed raw materials in decommissioned PV modules are Si, O, Na, Ca, Al and Mg, and the recyclable components in the raw materials are mainly metal silicon, Al_2O_3, SiO_2, Na_2O, CaO, MgO and Ag. X-ray diffraction analysis can see the X-ray diffraction peaks of metal Si, metal Al and Al_2O_3 in the silicon wafer. Because the glass is an amorphous substance, there are no obvious diffraction peaks of SiO_2, Na_2O, CaO and MgO.
2. The mixed particles of flaky silicon and polyhedral glass are subjected to gravity, friction and inertial force during the vibration separation process of the inclined separation platform, and the mixed particles of silicon wafers and glass follow Newton's law of motion during the vibration separation movement. The three forces of gravity, friction and inertia on the particles are superimposed, which is expressed as the force size and movement direction of the silicon wafer and glass. For silicon wafer particles, there is a friction coefficient $\mu \geq \cos\theta/\sin\theta$, for glass particles, then the friction coefficient $\mu \leq \cos\theta/\sin\theta$.
3. Through the experimental research on the new technology of vibration separation of silicon wafer and glass, the optimal conditions of feed particle size +3mm, feed amount 0.15 t/h, vibration voltage 190 V, vibration frequency 48 Hz, platform horizontal inclination angle 8°, and longitudinal inclination angle 3° were obtained. Under these optimized conditions, good experimental results are obtained: the content of metal Si in the obtained silicon wafer product is 84.47%, the recovery rate of metal Si is 83.73%, the content of impurity SiO_2 is 1.09%, and the content of SiO_2 in the glass product

is 65.69%, and the SiO_2 recovery rate is 98.95%, the impurity metal Si content is 0.56%. This study provides a research idea for the industrial separation of silicon wafers and glass from decommissioned PV modules.

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