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Design of Automatic Grinding and Painting Equipment for Reactors

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Abstract: To address the current problems in the reactor surface treatment industry, such as high manual dependence, low efficiency, unstable spraying quality, and harsh working environments, this study designs and develops an automatic grinding and painting device for reactors that integrates transport support, precision grinding, and multi-sided painting functions. The device adopts a modular design concept and achieves full-process automation of reactor surface treatment through the organic integration of a precision mechanical structure and an intelligent control system. It is adaptable to the complex structures of large reactors, meets high-precision processing requirements, and employs environmentally friendly treatment processes to effectively improve the working environment. The outcomes of this research not only solve the industry pain point of low automation in reactor surface treatment, significantly improving production efficiency and product quality, but also provide an efficient, environmentally friendly, and safe intelligent solution for the power equipment manufacturing industry, demonstrating important practical value and broad application prospects.

1. Introduction

In recent years, with the rapid development of the ultra-high voltage (UHV) power grid and the new energy industry, reactors, as key power equipment, have seen continuously increasing demands on the quality and efficiency of their surface grinding and painting processes [1]. Traditional manual operations suffer from low efficiency, unstable quality, and harsh working environments, which have become bottlenecks in the industry's development. Although China has a large-scale reactor manufacturing industry, the surface treatment segment remains heavily dependent on manual labor, facing challenges such as rising labor costs, low standardization of operations, and prominent environmental protection and safety risks [2].

In developed countries, companies such as ABB (Switzerland) and KUKA (Germany), relying on intelligent robots, 3D vision, and high-precision control technologies, have achieved mature automatic grinding and painting technologies for reactors, with automation rates exceeding 80% and advanced environmentally friendly processes. However, their equipment is expensive and poorly adaptable, making it difficult to fit the market pattern dominated by small and medium-sized enterprises in China. Domestically, although some technologies have been replaced by local alternatives, the localization rate of high-end equipment is less than 20%, core technologies still rely on imports, the industry's automation rate is below 50%, the proportion of solvent-based coatings remains high, and the implementation of environmental standards lags behind [3].

To address these industry pain points, we have designed this automatic grinding and painting equipment for reactors, aiming to promote the upgrade of power equipment manufacturing toward high efficiency, intelligence, and green development.

2. Scheme Design

2.1 Overall Scheme Design

By integrating functional modules such as transport support, precision grinding, and multi-sided painting, combined with intelligent conveying positioning and high-precision grinding control technologies, this product achieves efficient and automated surface treatment for reactors of different specifications, significantly improving production efficiency and spraying quality stability in power equipment manufacturing [4]. The device features a compact structure and a high degree of automation. It is not only suitable for large-scale production in major power equipment manufacturing enterprises but also accommodates the practical needs of small and medium-sized reactor processing companies, greatly reducing labor costs and operational risks while enhancing the precision and uniformity of product surface treatment [5]. The device mainly consists of three functional modules: the transport support module adopts an adjustable positioning and conveying mechanism to achieve precise transfer and station fixing of reactors; the grinding module combines a high-precision actuator and adaptive grinding technology to ensure the accuracy and consistency of reactor surface treatment; the painting module employs a multi-degree-of-freedom spraying system and environmentally friendly paint supply technology to achieve uniform multi-sided spraying of reactors after grinding. The drive system uses multi-motor coordinated control to ensure synchronous and efficient operation of all modules.

2.2 Transport Support Module

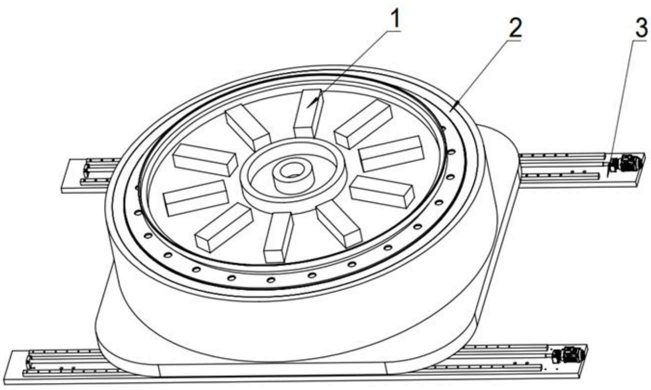

Figure 1: Transport support module: 1- Electromagnetic chuck; 2- Rotating platform; 3- Guide rails at both ends.

Through integrated design, this product achieves precise conveying and stable support for reactors of different specifications. The transport support module of this product includes guide rails at both ends, a rotating platform, and an electromagnetic chuck [6], as shown in Figure 1. The guide rails are arranged on both sides of the equipment frame, the rotating platform is mounted on the guide rails at both ends, and the electromagnetic chuck is built into the rotating platform. The conveying stroke of the guide rails and the rotation angle of the rotating platform can be adjusted according to different reactor specifications and processing requirements, enabling precise positioning and multi-sided machining under different working conditions [7].

The rotating platform adopts an integrated design:

(1) Turntable

The rotating platform uses a three-phase asynchronous motor as the power source. First, the horizontal power output by the motor is converted into vertical power via a bevel gear and transmitted upward. After the torque output is increased through a reduction gearbox, the power is then transmitted to the slewing bearing via the meshing drive of a planetary gear set. A cushion layer with universal balls under the slewing bearing ensures smooth rotation of the turntable by utilizing rolling friction. The turntable, which contains the electromagnetic chuck, is connected to the slewing bearing by bolts, ultimately driving the reactor to complete a rotary motion [8], as shown in Figure 2 below.

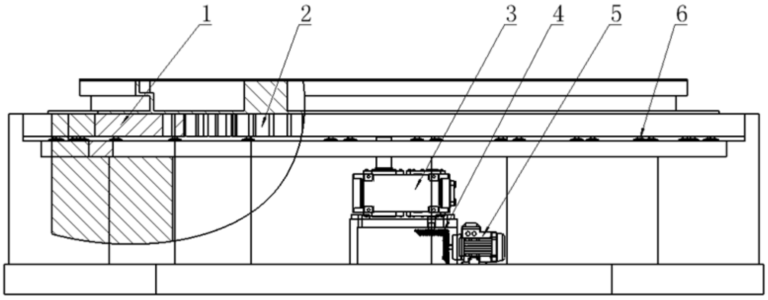

Figure 2: Rotating platform: 1- Slewing bearing; 2- Planetary gear set; 3- Reduction gearbox; 4- Bevel gear; 5- Bevel gear; 6- Universal ball.

(2) Electromagnetic chuck

Inside the electromagnetic chuck, winding blocks are uniformly arranged along the circumferential direction, with coils neatly wound around each winding block. When energized, the coils generate a stable holding force, firmly fixing the reactor by magnetic attraction, tightly combining the reactor with the rotating platform, and enabling both to rotate synchronously [6].

The two components operate simultaneously, balancing efficiency and precision. Moreover, the parametric design allows the equipment to flexibly adapt to different reactors, providing an efficient solution for reactor grinding and painting.

2.3 Grinding Module

This product adopts an innovative precision grinding device, including a lifting table, a robotic arm, and a dust-collecting grinding head, as shown in Figure 3. The lifting table, robotic arm, and dust-collecting grinding head work together to achieve efficient and precise grinding of the reactor surface [5]. The lifting table consists of a lead screw guide rail, a lead screw motor, and a lead screw slider. The lead screw motor is located at the top as the drive, and the lead screw slider cooperates with the lead screw to drive the robotic arm up and down. The robotic arm comprises an upper arm and a forearm. The upper arm is connected to the lead screw slider, and the forearm is connected to the support plate of the dust-collecting grinding head. Both arms have two rotational degrees of freedom, allowing opening and closing movements according to the reactor's position, slowly approaching the reactor until reaching the designated grinding position [9]. The dust-collecting grinding head includes a grinding disc, a stepper motor, sensing components, a support plate, and a vacuum cleaner. The grinding disc is connected to the motor shaft, while the motor and sensing components are placed inside the support plate. The vacuum head of the cleaner covers the entire support plate, with only the grinding disc exposed. When the stepper motor starts, it drives the grinding disc to perform grinding. The sensing components feedback pressure values through mechanisms such as springs, sliders, and sensors, thereby controlling the feed rate of the robotic arm to achieve pressure-regulated grinding and precise results. Meanwhile, the vacuum cleaner operates normally during grinding, absorbing the dust generated. This dynamically achieves precise grinding of the reactor surface and dust recovery, ensuring grinding accuracy and a clean working environment, thus laying the foundation for the subsequent painting process.

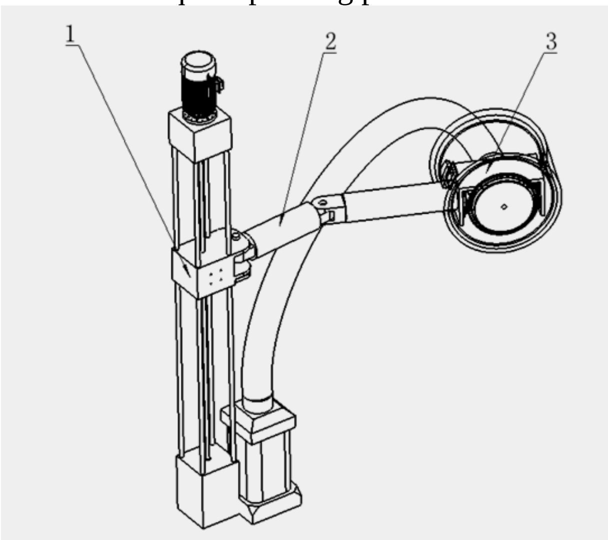

Figure 3: Grinding module: 1- Lifting table; 2- Robotic arm; 3- Dust-collecting grinding head.

(1) Lifting table

The high-precision lead screw guide rail, combined with the lead screw motor and slider drive design, uses the top lead screw motor as the drive to move the slider along the guide rail for lifting motion [9]. Since reactor specifications vary, the lifting table precisely adjusts the height of the robotic arm to effectively adapt to the grinding positions of different reactor specifications without causing interference.

(2) Robotic arm

A two-degree-of-freedom segmented design with an upper arm and a forearm is adopted. The upper arm is connected to the slider, and the forearm is connected to the grinding head. After the lifting table reaches the required position, the arm performs opening/closing and feeding motions according to the reactor position [9]. The adjustable degrees of freedom of the arm ensure flexible approach to the reactor while adapting to the grinding posture requirements of its complex structure.

(3) Dust-collecting grinding head

The stepper motor starts, driving the grinding disc to contact the side of the reactor and perform grinding. The pressure generated during grinding is transmitted from the grinding disc to the connecting plate, and then through the connecting plate to the slider, causing the spring to compress and deform. The spring deformation is fed back to the sensor to obtain real-time pressure values. The control system then adjusts the feed rates of the upper arm and forearm according to these values, achieving precise regulation of grinding pressure for high-precision grinding. Meanwhile, the vacuum cleaner operates synchronously throughout the grinding process, performing real-time dust collection and treatment [10], as shown in Figure 4 below.

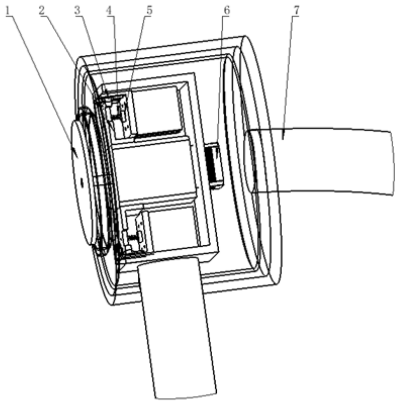

Figure 4: Dust-collecting grinding head: 1- Grinding disc; 2- Connecting plate; 3- Slider; 4- Spring; 5- Sensor; 6- Stepper motor; 7- Dust suction tube.

2.4 Painting Module

This product adopts an innovative multi-sided spraying device, including two sets of multi-direction spraying slide shoes, multiple sets of lead screw guide rails, a spraying linkage rod, and spray guns, enabling comprehensive and uniform spraying of the reactor surface [11], as shown in Figure 5. The first spraying slide shoe contains a first lead screw guide rail, and the second spraying slide shoe contains second, third, fourth, and fifth lead screw guide rails. Each guide rail works cooperatively to drive the movement of the spray guns.

When the rotating platform is in operation, the fourth and fifth lead screw guide rails are activated to move the second spray gun to an appropriate position, spraying the side of the reactor from bottom to top. After completing the side spraying, the platform rotation is stopped, the second and third lead screw guide rails are activated to move the spraying linkage rod, and then the first lead screw guide rail is used to extend into the interior of the reactor to apply paint to the inner wall from bottom to top. This device dynamically achieves uniform multi-sided spraying on both the external surface and the interior of the reactor, laying the foundation for improving its insulation performance and corrosion resistance.

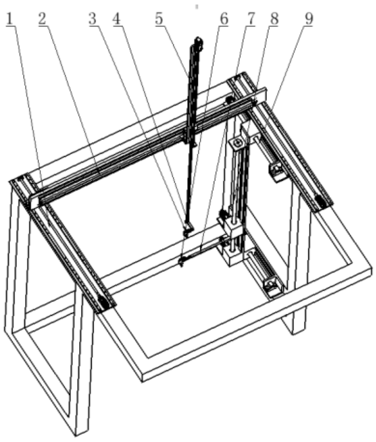

Figure 5: Painting module: 1- First lead screw; 2- Second lead screw; 3- First telescopic rod; 4- First spray gun; 5- Third lead screw; 6- Second spray gun; 7- Second telescopic rod; 8- Fourth lead screw; 9- Fifth lead screw.

(1) Spray gun

Dual spray gun configuration equipped with infrared distance measurement function. After the transmission mechanism reaches position, it performs bottom-to-top painting operations on the side and inner wall of the reactor respectively [4], as shown in Figure 6. The distance measurement feedback enables precise control of the spraying distance, ensuring uniform coating thickness and efficiently meeting the differentiated painting requirements of the reactor's external surface and internal cavity.

(2) Telescopic rod

A telescopic structure that cooperates with the spray guns and lead screw guide rails, performing fine adjustment of the spray gun position during the painting process in coordination with the guide rails [12]. The telescopic length can be flexibly adjusted, effectively compensating for the limitation of fixed guide rail stroke, precisely matching the painting points of reactors of different specifications, and improving the adaptability of the device.

(3) Lead screw guide rails

Multiple sets of high-precision transmission components arranged in vertical and horizontal orientations, each driving the spray guns, telescopic rods, and spraying linkage rod to perform multi-dimensional movements [13]. With high transmission precision and strong operational stability, the multiple sets work together to achieve omnidirectional positioning of the spray guns, providing precise displacement support for multi-sided painting of both the interior and exterior of the reactor.

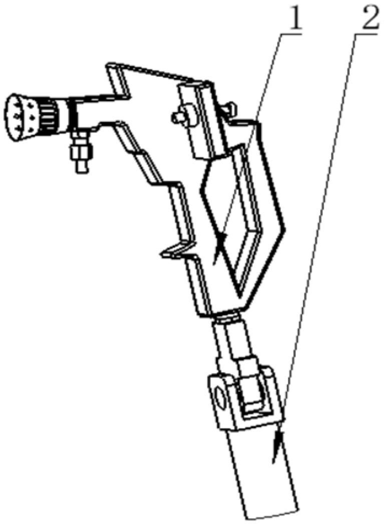

Figure 6: Spray gun: 1- Spray gun; 2- Telescopic rod

2.5 Selection of Power Equipment

2.5.1 Turntable Motor Selection

The selection of the motor and reducer is mainly based on three aspects: torque, power, and transmission ratio. See Table 1 for motor and reducer selection.

Table 1: Motor and reducer selection

Parameter	Calculated value	Selected value	Remarks
Turntable design speed $n_{turntable}$	3 r/min (assumed)	3 r/min	Common speed for reactor rotary grinding/painting
Load mass m	20 t	20 t	Rated load of reactor on turntable
Rolling friction	0.005	-	Common engineering value for universal ball

coefficient f	(assumed)		cushion layer rolling friction
Turntable rotation radius R	2 m (assumed)	-	Matching reactor rotating platform diameter specification
Total transmission efficiency η_{total}	0.8 (assumed)	-	Total efficiency including planetary gear train, reducer, slewing bearing
Safety factor K_1	1.5	-	Torque verification safety factor
Impact factor K_2	1.2	-	Equipment operation impact condition factor
Motor rated speed n_{motor}	1440 r/min	1440 r/min	Standard speed of three-phase asynchronous motor
Planetary gear train ratio $i_{planetary}$	4	4	Known planetary transmission ratio
Total transmission ratio i_{total}	480	480	Converted from motor and turntable speeds
Reducer transmission ratio $i_{reducer}$	120	120	Matching total ratio and planetary ratio
Turntable required torque $T_{turntable}$	3528 N·m	-	Core torque for load drive
Motor output torque T_{motor}	9.23 N·m	-	Motor demand after conversion by ratio and efficiency
Motor calculated power P	1.51 kW	11 kW	Oversized selection considering operational redundancy

(1) Calculation of the required torque $T_{turntable}$ for the turntable

The turntable is driven by rolling friction. The core torque formula:

$$T_{turntable}=m\times g\times f\times R\times K_1\times K_2 \quad (1)$$

In equation (1): g = 9.8 m/s² is the acceleration due to gravity; K_1 is the safety factor; K_2 is the impact factor. From Table 1: m = 20000 kg, f = 0.005, R = 2 m, K_1 = 1.5, K_2 = 1.2. Substituting into equation (1) yields:

$$T_{turntable}=20000\times9.8\times0.005\times2\times1.5\times1.2=3528\ N\cdot m$$

(2) Calculation of the total transmission ratio i_{total} and the reducer transmission ratio $i_{reducer}$

The total transmission ratio is determined by the rated speed of the motor and the design speed of the turntable.

$$i_{total}=\frac{n_{motor}}{n_{turntable}} \quad (2)$$

From Table 1: n_{motor} = 1440 r/min, n_turntable = 3 r/min. Substituting into equation (2) gives:

$$i_{total}=\frac{1440}{3}=480$$

Given that the planetary gear train transmission ratio $i_{planetary}$ = 4, the reducer transmission ratio is:

$$i_{reducer}=\frac{i_{total}}{i_{planetary}}=\frac{480}{4}=120$$

(3) Calculation of motor output torque T_{motor}

The motor output torque must meet the turntable torque requirement, considering transmission efficiency:

$$T_{motor}=\frac{T_{turntable}}{i_{total}\times\eta_{total}} \quad (3)$$

From Table 1: T_turntable = 3528, i_total = 480, η_total = 0.8. Substituting into equation (3) gives:

$$T_{motor}=\frac{3528}{480\times0.8}\approx9.23\ N\cdot m$$

(4) Calculation of motor rated power P

Relationship between power, torque, and speed for three-phase asynchronous motors

$$P=\frac{T_{motor}\times n_{motor}}{9550\times\eta_{total}} \quad (4)$$

(In equation :9550 is the power-torque conversion coefficient; η_motor = 0.9 is the motor's own efficiency)

From Table 1: T_{motor} = 9.23, n_{motor} = 1440 r/min. Substituting into equation (4) gives:

$$P=\frac{9.23\times1440}{9550\times0.9}\approx1.51kW$$

Considering continuous operation and load fluctuations under grinding/painting conditions, the actual selection is enlarged to 11 kW (to accommodate the long-term operation redundancy for a 20-ton heavy load).

(5) Reducer selection verification

The allowable torque of the reducer must satisfy:

$$T_{Reducer\ selection\ verification}\geq T_{turntable}\times K_1=3528\times1.5=5292\ N\cdot m$$

During selection, choose a hardened-gear reducer with an allowable torque ≥ 6000 N·m, a transmission ratio matching 120, and a vertical flange mounting configuration (suitable for vertical power input of the rotating platform).

2.5.2 Grinding head motor selection

For the selection of the grinding head motor, a servo motor that is easy to install is preferred (suitable for the compact structure of the grinding head, offering convenient installation and precise positioning; it provides better low-speed stability than a stepper motor and does not require an additional reducer, simplifying the installation process). The selection is mainly based on three aspects: rated torque, rated power, and rated speed. It must match the actual working conditions of reactor surface grinding to ensure grinding efficiency and precision. See Table 2 for the grinding head motor selection.

Table 2: Grinding head motor selection

Parameter	Calculated value	Selected value	Remarks
Grinding head design speed n grinding $\eta_{grinding}$	1500 r/min(actual working condition)	1500 r/min	Suitable speed for reactor surface grinding (avoiding scratching at too high speed or incomplete grinding at too low speed)
Grinding load resistance F	80 N	-	Common load for reactor surface grinding (rust removal / deburring)

Grinding disc radius r	0.15 m	-	Conventional grinding disc specification suitable for reactor surface grinding
Motor transmission efficiency $\eta_{\text{motor of grinding}}$	0.9	-	Direct connection between servo motor and grinding disc, high transmission efficiency, no additional reducer needed, reducing installation steps
Safety factor K_1	1.5	-	Torque verification safety factor (adapting to grinding load fluctuations)
Impact factor K_2	1.1	-	Working condition factor for slight impacts during grinding (uneven reactor surface)
Required torque for grinding head T_{grinding}	18 N·m	-	Core torque for driving the grinding head
Motor output torque $T_{\text{motor of grinding}}$	20 N·m	-	Motor demand after conversion by efficiency and safety factors, matching servo motor torque characteristics
Motor rated speed $n_{\text{motor of grinding}}$	1500 r/min	1500 r/min	Standard speed of servo motor, fully matching the grinding head design speed, no speed adjustment required
Motor calculated power P	3.16 kW	4 kW	Considering continuous grinding operation and load fluctuations, enlarged redundant selection to fit servo motor power specifications
Motor mounting type	-	Horizontal direct connection	Servo motor compact size, easy installation, directly drives the grinding disc rotation, suitable for grinding head structure

(1) Calculation of the required torque T_{grinding} for the grinding head

The grinding head torque is primarily used to overcome the grinding resistance on the reactor surface and to drive the rotation of the grinding disc. The formula is:

$$T_{\text{grinding}}=F\times r\times K_1\times K_2 \tag{5}$$

(In equation: F is the grinding load resistance; r is the radius of the grinding disc; K_1 is the safety factor; K_2 is the impact factor)

From Table 2: F = 80 N, r = 0.15 m, K_1 = 1.5, K_2 = 1.1. Substituting into equation (5) yields:

$$T_{\text{grinding}}=80\times 0.15\times 1.5\times 1.1=18\ N\cdot m$$

(2) Calculation of the grinding head motor output torque $T_{\text{motor of grinding}}$

A servo motor is selected (easy to install, no additional reducer required). The motor output torque must meet the torque requirement of the grinding head, considering the motor's own transmission efficiency. Formula:

$$T_{\text{motor of grinding}}=\frac{T_{\text{grinding}}}{\eta_{\text{motor of grinding}}} \tag{6}$$

(Where: $\eta_{\text{motor of grinding}}$ is the transmission efficiency between the servo motor and the grinding disc; the direct connection efficiency of the servo motor is higher than that of an ordinary asynchronous motor.) From Table 2: $\eta_{\text{motor of grinding}}$ = 0.9. Substituting into equation (6) yields:

$$T_{\eta_{\text{motor of grinding}}}=\frac{18}{0.9}=20\ N\cdot m$$

(3) Calculation of the rated power P of the grinding head motor

The relationship between servo motor power, torque, and speed follows the standard conversion formula, adapted to the characteristics of the servo motor:

$$P=\frac{T_{\eta_{\text{motor of grinding}}}\times n_{\eta_{\text{motor of grinding}}}}{9550\times\eta_{\text{motor}}} \tag{7}$$

(Where: 9550 is the power-torque conversion coefficient; η_motor = 0.92 is the servo motor's own efficiency, which is higher than that of ordinary three-phase asynchronous motors; n_motor_grinding is the rated speed of the motor)

$$P=\frac{20\times1500}{9550\times0.92}\approx3.16\ kW$$

Considering that reactor surface grinding requires continuous operation, load fluctuations may occur due to possible uneven protrusions on the surface, and the need for long-term stable operation of the servo motor, the actual selection is enlarged with redundancy. A 4 kW servo motor is selected to meet the actual grinding requirements while also taking into account ease of installation.

2.6 Structural Strength Analysis

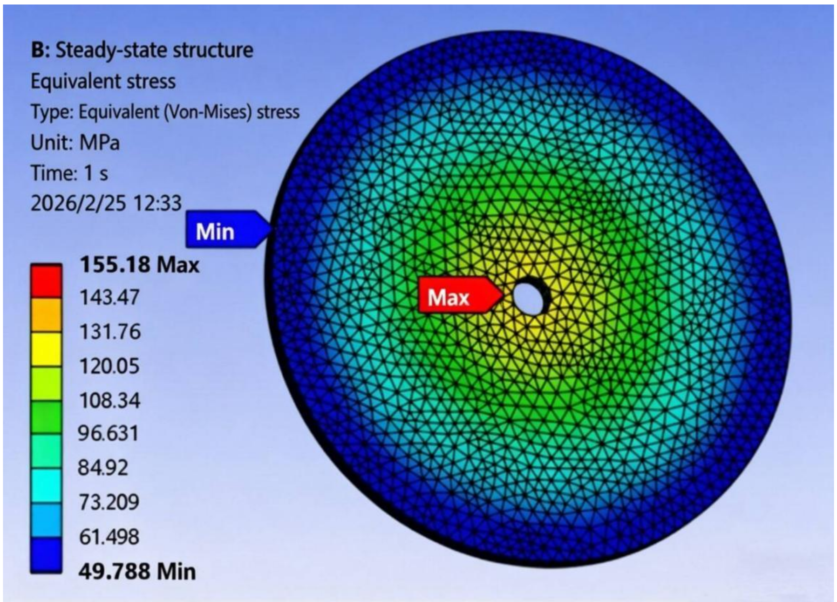

Figure 7: Stress analysis of the grinding blade

Structural strength analysis of key components is carried out to ensure safe and reliable operation of the equipment. Taking the grinding blade as an example, under the operating condition where the rated power is P=9550×0.9220×1500≈3.16kW, the rotational speed is n=1500r/min, and the blade surface is subjected to a pressure reaction force of approximately 46.3 N, the cutting reaction force and torque load are withstood. Finite element analysis is used to verify its strength and stiffness. As shown in Figure 7, the maximum equivalent stress is 155.18 MPa, which is far below the material’s yield strength, providing an adequate safety factor and meeting long-term working requirements.

3. Product Features and Advantages

Compared with existing reactor surface treatment processes, this product features a structural form that integrates surface grinding, rust and burr removal, uniform internal and external cavity spraying, and curing through the coordination of the rotating platform, grinding head, multi-directional spraying slide shoes, and planetary transmission system, enabling fully automated operation [1]. It reduces manual intervention, ensures precise operation, significantly saves time and cost, and makes the treatment work efficient and smooth, especially suitable for continuous processing of batch reactors [2]. The specific advantages are:

(1) Fully automated process. This product adopts a high-precision planetary transmission combined with a rotating platform to achieve fully automated flow of reactor grinding and painting processes. With the precise positioning of infrared distance measurement and multi-directional spraying slide shoes, it effectively avoids manual operation errors and greatly improves batch processing efficiency, particularly suitable for continuous production of reactors of various specifications [8].

(2) Precision grinding and burr removal. This product employs a combined design of a servo-driven grinding head and pressure feedback control. Under the operating conditions of rated speed 480 r/min and the blade subjected to a pressure reaction force of approximately 46.3 N, it effectively removes surface rust, burrs, and protrusions without damaging the reactor insulation layer, improving surface flatness and subsequent coating adhesion [4].

(3) Deep and uniform spraying. Through the synergistic action of multi-directional spraying slide shoes and infrared distance measurement, this product achieves uniform spraying without dead angles on both the external surface and internal cavity of the reactor. The coating thickness is controllable and highly consistent, effectively improving the product's insulation performance and corrosion resistance, ensuring electrical safety and service life [12].

(4) Efficient and stable operation. This product adopts a combined transmission structure of a planetary gear train and a hardened-gear reducer, together with precise control of the servo motor, enabling smooth rotation and continuous operation under a 20-ton heavy load. It features strong operational stability and low failure rate, meeting the high-load demands of industrial production [11].

(5) Flexible adaptation to multiple specifications. The spraying position, grinding parameters, and rotating platform of this product are all flexibly adjustable, making it suitable for reactors of different sizes and structural forms. It covers the processing needs of various specifications, greatly enhancing equipment versatility and production flexibility [13].

4. Conclusion

This equipment adopts a highly integrated modular design, and has successfully developed an intelligent reactor surface treatment device integrating precise surface grinding, rust and burr removal, uniform spraying of internal and external cavities, and real-time dust collection. It precisely meets the market's urgent demand for efficient and integrated processing equipment. In addition, the equipment innovatively applies a servo-driven grinding system, a pressure feedback regulation device and a multi-directional spraying slide shoe structure, which can flexibly adapt to reactors of various specifications. It effectively enhances the treatment efficiency and automation level, reduces labor costs and operational difficulties, and provides a comprehensive and reliable solution for the reactor manufacturing industry. The overall model is shown in Figure 8.

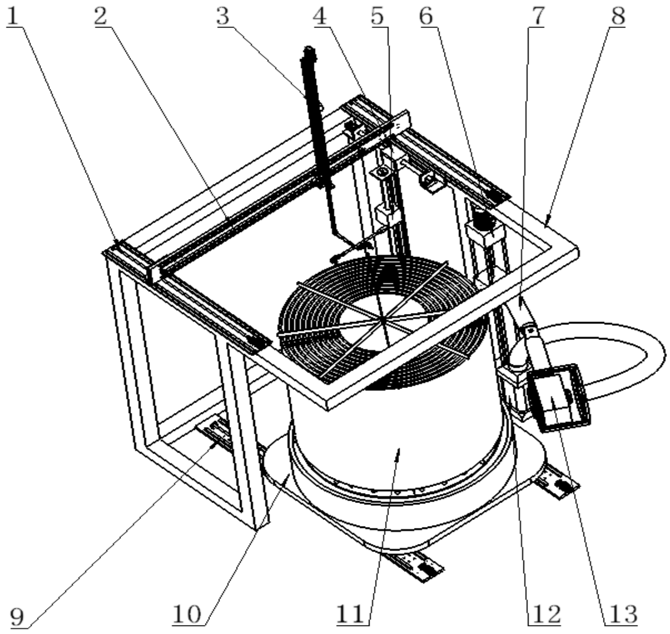

Figure 8: Overall structure: 1- First lead screw; 2- Second lead screw; 3- Third lead screw; 4- Fourth lead screw; 5- Fifth lead screw; 6- Lifting table; 7- Robotic arm; 8- Bracket; 9- Guide rails; 10- Rotating platform; 11- Reactor body; 12- Vacuum cleaner; 13- Dust-collecting grinding head.

Acknowledgement

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