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Co-design and Application Progress of Compound Surface Solar Concentrators and Tracking Mechanisms

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Abstract:

With the increasing global demand for clean energy, the efficient utilization of solar energy has become a research hotspot. As fossil fuel depletion and environmental pollution intensify, solar energy stands out as a sustainable and eco-friendly alternative, driving advancements in solar concentration technologies. This paper focuses on the collaborative design of composite surface solar concentrator and its tracking mechanism, systematically combining the structure type of composite surface concentrator, optical design theory, as well as the type and control strategy of the tracking mechanism. Combined with solar photovoltaic power generation, solar thermal utilization, and other practical application cases, it is verified that the co-design can significantly improve the solar energy utilization efficiency and reduce the system cost. The results provide theoretical support and practical reference for the optimal design and popularization of composite surface solar concentrator systems, which is of great significance to promote the development of the solar energy industry.

Keywords: Concentrator, Solar Position Tracking Mechanism, Solar Energy

1. Introduction

Solar energy, as a clean and renewable energy source, produces almost no greenhouse gases and other pollutants in the power generation process. The development and utilization of solar energy is regarded as an important way to solve energy and environmental problems. However, solar energy has its own defective characteristics such as low energy density and strong intermittency, which limits its large-scale and efficient utilization to a certain extent, so people have begun to study the composite curved solar concentrator. The constantly changing position of the sun makes it difficult for the concentrator to always maintain the optimal concentration effect, so the synergistic design of the tracking mechanism is crucial. Composite curved concentrator can converge the large area of sunlight to a smaller receiving surface, to improve the energy flow density of the receiving surface。 Tracking mechanism can adjust the orientation of the concentrator in real time, so that it is always aligned with the sun. The synergistic work of the two can significantly improve the efficiency of concentrating light. At present, the main types of solar energy collection systems include dish-type, trough-type, tower-type and photovoltaic systems [1].

Han Feng et al. proposed a new trapezoidal multifocal Fresnel lens concentrator design method, which improved the light concentration efficiency and uniformity [2]. Yi Yunfan et al. constructed an asymmetric composite planar concentrator model for vacuum tube absorber, which provides a new idea for concentrator design [3]. Chang Zehui et al. used TracePro software to simulate and analyze the effect of absorber shape on the optical performance of composite multi-surface concentrator, which provided a basis for the optimal design of the concentrator [4]. Hu Yanru et al. designed an automatic light chasing system based on microcontroller to realize real-time tracking of the sun's position [5]. Su Shuangqin et al. used SMT microcontroller to design a dual-axis solar intelligent light chasing system, which improved the degree of intelligence and accuracy of tracking [6]. Meanwhile, scholars have also studied the effects of different tracking methods, such as single-axis tracking and dual-axis tracking, on the performance of the concentrator, as well as the synergistic control strategy of the tracking mechanism and the concentrator.

The purpose of this paper is to analyze the theory and application of the synergistic design of composite surface solar concentrator and tracking mechanism. It aims to improve the theoretical system of the co-design of compound curved surface solar concentrator and tracking mechanism, to provide new ideas and methods for the research in the field of solar energy utilization, to understand the physical process and internal mechanism of solar energy concentrating and tracking in a more comprehensive way, and to promote the development of related disciplines.

2. Composite Curved Surface Solar Concentrator with Tracking Mechanism Synergy

The composite curved surface concentrator expands the effective reception angle of sunlight through its specially designed curved structure, while the tracking mechanism adjusts the azimuth and altitude angles of the whole device in real time to accurately align with the sun's position. The two work together to enable the concentrator to continuously and efficiently converge solar radiation from a large area onto a small area of photovoltaic cells or heat collectors under more generous tracking accuracy requirements, thus significantly improving the system's light energy capture efficiency and output power.

2.1 Classification of Compound Curved Surface Solar Concentrators

2.1.1 Cylindrical Surface Mirror Splicing Trough Solar Concentrator

Cylindrical Mirrors Splicing Trough Solar Concentrator utilizes the principle of reflection to focus solar energy by splicing multiple cylindrical mirrors into an approximate parabolic shape. The core idea is to simulate the optical properties of a paraboloid through splicing mirrors, while reducing the manufacturing complexity and cost of traditional parabolic mirrors. The center of each cylindrical mirror is located on the parabola, and its center normal vector coincides with the normal vector of the parabola at that point. This allows the light reflected from each mirror to converge approximately to the focus of the parabola, forming a linear focus. The reflected light converges to either a CavityReceiver or a TubeReceiver located at the focus. The CavityReceiver is suitable for high temperature scenarios (e.g. 400°C) due to its low heat loss, while the TubeReceiver is simple in construction but has a high heat loss.

In a columnar mirror array, the column mirror unit consists of a plurality of narrow strip-like column mirrors spliced together, with the centers aligned along a parabola to form an approximate parabolic reflective surface. For the support structure, lightweight materials are usually used to reduce cost and structural deformation, such as aluminum alloy.

2.1.2 Water-filled Fresnel Concentrator

Conventional Fresnel concentrators use transparent organic materials, such as PMMA, or glass as the lens material, and the cost rises significantly with increasing size. The water-filled concentrator reduces costs by replacing most of the lens material with pure water, retaining only thin flat glass as the structural support, and utilizing the refractive properties of water to achieve light concentration, reducing material consumption while maintaining optical performance.

The concentrator consists of a series of hollow, right-angled triangular prisms, each consisting of three pieces of thin plate glass filled with pure water. Sunlight passes through the air-glass, glass-water, water-glass, and glass-air interfaces in sequence, undergoing multiple refractions. By designing the inclination angle of the tri-prism, the light rays are converged on a receiving target at the focal line.

The basic unit is a hollow right-angled tri-prism, consist-

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ing of three pieces of thin flat glass, which form the three faces of the tri-prism, and the material can be chosen from ordinary glass or organic glass. The interior of the hollow cavity is filled with pure water as the main light-transmitting medium. The prisms are secured by serrated steel beams to provide structural support and maintain prism spacing.

2.1.3 New Trapezoidal Multifocal Fresnel Lens Concentrator

The concentrator enhances its performance through the dual mechanism of optical focusing and heat flow homogenization. The core principles include focal point dispersion, reflector-assisted focusing, and heat source simulation with coupled strains. Each tri-prism corresponds to a small arc segment on the upper surface of the collector, and calculating the angle of inclination of the tri-prism by Snell‘s law ensures the light focused directly to the corresponding arc segment, ensuring that each arc segment receives the same energy and realizing the homogenization of heat flow on the upper surface. The light is refracted by the horizontal tri-prism and then focused to the reflector, and then reflected to the collector tube. The coordinates of the reflection points are optimized by a recursive method to match the density of heat flow on the lower surface with that on the upper surface to avoid local overheating.

The concentrator is mainly composed of three parts: Fresnel lens, reflector and collector tube, adopting a symmetric trapezoidal structure, and the core design is to divide the lens into a horizontal lens section and a tilted lens section, which control the focusing path of light to realize the uniform dispersion of the focal point respectively.

2.1.4 Round Tube CPC

Designed based on the fringe ray principle in geometric optics, it ensures that all incident light within the receiving angle is reflected and converged onto the receiving tube. The core objective is to realize the efficient capture and convergence of solar rays without the need for a complex tracking system.

The concentrator mainly consists of a reflecting surface, a receiving tube and a glass cover. The reflecting surface consists of two parts, the involute and parabolic, where the involute part guides the fringe rays towards the receiver tube and the parabolic part further reflects the rays to the receiver tube, and the interception operation is mainly aimed at the parabolic part. The receiver tube is usually a vacuum tube containing a U-shaped aluminum tube and aluminum fins to absorb the converging light energy and transfer it to the work material (e.g., water). A glass cover covers the reflective surface to minimize heat loss and protect the internal structure.

Increasing the receiver half-angle improves optical efficiency, but increases interstitial leakage losses. Reducing the radius of the receiver tube reduces the leakage loss, which is especially effective for CPC concentrators with a small receiver half-angle.

2.1.5 Compound Eye Static Solar Concentrator

The compound-eye static solar concentrator is mainly composed of two parts, namely, the bionic compound-eye shell and the secondary concentrator, and realizes large-angle light collection and high-efficiency convergence by simulating the multi-channel optical structure of the compound-eye of insects.

The bionic compound eye shell receives light through multiple channels. Each sub-eye on the surface of the compound eye shell receives sunlight at different angles (including direct light and diffuse scattered light) independently during the light collection stage, and then utilizes the law of refraction to converge the light to the bottom of the shell. At the same time, the curved arrangement of the sub-eye arrays allows the concentrator to receive light at angles beyond the limitations of conventional concentrators that need to track the sun.

The secondary concentrator is used to converge the light collected by the compound eye spherical shell. The light cone concentrator converges the light from the sub-eye into the large end of the light cone, which is reflected by the inner wall and propagates to the small end, and finally focuses on the solar cell. The reflection process reduces energy loss by minimizing the number of reflections. Composite parabolic concentrator utilizes the optical properties of parabolic surface, the edge light is reflected by the parabolic surface and converged to the small end.

2.2 Categories and Control Strategies of Tracking Mechanism

The tracking system is of great significance for the compound curved surface solar concentrator. It can precisely adjust the angle and position of the concentrator, continuously track the position of the sun to maximize the concentration efficiency, optimize energy collection, and ensure the stable operation of the system, thereby enhancing the overall performance and energy output of the compound curved surface solar concentrator.

2.2.1 Categories of Tracking Mechanism

Tracking mechanisms can be broadly classified into two-axis tracking mechanisms, single-axis tracking mechanisms, parallel mechanism tracking, and photoelectric sensor-driven tracking.

The dual-axis tracking mechanism synchronously adjusts the solar elevation angle and azimuth angle to ensure that the incident light is perpendicular to the concentrating surface, significantly enhancing the heat collection efficiency. For instance, the McDonnell Douglas system in the United States employs dual-axis tracking and achieves high-precision concentrating. However, its structure is complex, the cost is high, and its stability is poor under wind load conditions. It is suitable for experimental research or small-scale, high-precision scenarios [7].

The single-axis tracking mechanism is adjusted by a single rotating axis, with low cost and a simple structure, and is suitable for large-scale applications. Among them, for the north-south inclined type, Zhang Yunpeng et al. found that when the inclination angle β in Shanghai is 28.67°, the annual radiation reception can reach 94.46% of that of the dual-axis systems [8]. While for the north-south axial type, the inclination angle is fixed at the local latitude (such as in Lhasa, β = 27.29°), the stability is high but the efficiency fluctuates greatly [9]. The single-axis tracking mechanism is adjusted by a single rotating axis, with low cost and a simple structure, and is suitable for large-scale applications. Among them, for the north-south inclined type, Zhang Yunpeng et al. found that when the inclination angle β in Shanghai is 28.67°, the annual radiation reception can reach 94.46% of that of the dual-axis system [8]. While for the north-south axial type, the inclination angle is fixed at the local latitude (such as in Lhasa, β = 27.29°), the stability is high but the efficiency fluctuates greatly [9]. The horizontal structure is the simplest but has the lowest efficiency (such as the east-west horizontal type, the annual radiation quantity is only 76.63% of that of the dual-axis system) [8].

For parallel mechanism tracking, the 3-RPS parallel mechanism adjusts the position and posture of the moving platform through the coordinated adjustment of multiple chains, featuring high stiffness and no accumulation of errors. Liu Fanmao et al. optimized the radius of the fixed platform using a genetic algorithm to 860mm, increasing the overall dexterity by 24.9% and the stiffness by 16.7%, making it suitable for disc-type concentrating devices (such as the 38kW device of China Oilfield Group) [10].

For the drive and tracking of photoelectric sensors, the system designed by Hu Yanru et al. detects the light differences through four-directional photoresistors and combines with the STC89C52 single-chip microcomputer to adjust the direction in real time. In sunny weather, the tracking error is less than 5°. The hardware cost is low and it is suitable for household photovoltaic systems [5].

2.2.2 Control Strategies of Tracking Mechanism

Jia Danping et al. proposed using photoelectric tracking on sunny days and switching to the solar trajectory algorithm on cloudy days (based on Spencer ecliptic angle model), with the error controlled within 0.65 minutes, suitable for cloudy areas [9]. Wang Heng proposed the variable step size interference observation method [11]. At a long distance, a large step size ($\Delta D = 0.01$) is used to accelerate tracking, and at a short distance, a small step size ($\Delta D = 0.001$) is switched to reduce oscillation, enabling the system to increase power to 100W within 0.02 seconds, with an efficiency increase of 12% compared to traditional algorithms. Liu Fanmao et al. optimized the fixed platform radius through genetic algorithms and combined with ANSYS verification, achieving a 24.9% improvement in global dexterity and a 16.7% increase in stiffness, providing theoretical support for high-precision concentrating systems [10]. Zhang Xudong et al. designed a single-axis tracking system that calibrates the elevation angle every 15 minutes using a timer, with an error of less than 1.5°. Combined with the lower computer OK6410 module, it realizes data acquisition and processing [12].

2.3 Collaborative Cooperation Scheme and Influence

2.3.1 Collaborative Cooperation Scheme

The dual-stage concentrating technology, through innovative optical path design, effectively enhances the concentrating efficiency and the tolerance range of the incident angle without excessively increasing the complexity of optical components. It is particularly suitable for heat collection scenarios with medium to high temperatures (200-500°C). The core breakthroughs lie in two paths: The first is the cylindrical mirror splicing trough-type technology, which uses segmented flat or small curvature cylindrical lenses to simulate an overall parabolic surface (primary reflection) and is combined with a precise tracking system for dynamic fine-tuning (secondary enhancement), significantly reducing the manufacturing difficulty of traditional large parabolic surfaces; the second is the trapezoidal multi-focal Fresnel lens technology, where the inclined section directly refracts and focuses the light onto the upper surface (primary refraction), while the horizontal section reflects the light twice to focus it onto the lower surface (secondary reflection). This unique dual-path design not only achieves the uniformity of heat flow but also increases the concentrating ratio to 1.8 times that of the traditional single-stage system.

2.3.2 Influence of the Mechanism Technology

In terms of absorber optimization, the core technological breakthroughs focus on uniform heat flow and heat loss control: For the cylindrical mirror assembly scheme, a closed cavity-type receiver structure was adopted, effectively reducing convective heat loss in high-temperature

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scenarios, and increasing the thermal efficiency by 12%-15% compared to traditional tubular receivers; In the trapezoidal Fresnel scheme, through a unique focus dispersion design (each ridge tooth corresponding to a specific arc segment) combined with the assistance of the reflector for focusing, the deviation of heat flow density on the upper and lower surfaces of the heat collection tubes was controlled within 5%, significantly avoiding the problem of material aging caused by local overheating; In addition, the circular tube type CPC concentrator innovatively combines vacuum tubes, U-shaped aluminum tubes and aluminum fins, and adopts a composite reflecting surface of involute-parabola. Without the need for tracking, it achieved a good balance between optical efficiency and heat absorption efficiency, significantly reducing light leakage loss to below 8% (traditional design was approximately 15%). These optimization measures ultimately increased the overall thermal efficiency of the system by 10%-20%, effectively extending the equipment lifespan and reducing maintenance costs.

In terms of tracking and alignment technologies, the innovation lies in dynamic response and cost compatibility: For the cylindrical mirror assembly scheme, a single-axis tracking system with a lightweight (aluminum alloy-supported) structure is used for north-south axis rotation to achieve real-time and precise alignment with the sun (tracking error < 0.5°), and its cost is 40% lower than that of a dual-axis system, making it highly suitable for small and medium-scale concentrating applications; for the water injection Fresnel and trapezoidal Fresnel schemes, fixed-angle optimization or symmetrical structural design is adopted to achieve untracked operation, completely avoiding complex tracking mechanisms, and is particularly suitable for distributed power generation or civilian hot water systems, with installation costs reduced by more than 50%. This ability to flexibly configure tracking strategies based on application requirements - active tracking in high-yield scenarios (such as industrial heating) and passive alignment in low-cost scenarios - has greatly enhanced the universality and scene adaptability of solar energy technology.

3. Materials and Manufacturing Technology

In the design and manufacturing of composite curved surface solar concentrators, the selection of materials and the optimization of processes are of crucial importance for improving the system performance. Regarding the reflective materials, the model of the composite parabolic concentrator with an arc-shaped absorber uses a high-reflection rate flexible concentrating reflective film (with a reflection rate > 90%) to cover the reflective surface, significantly enhancing the light reflection efficiency [13]. For the concentrator design considering the solar angle, the aluminum mirror is used as the reflective substrate, and through the surface coating process, a mirror reflection rate of 94.8% is achieved [14]. The research on photothermal conversion materials shows a diversified trend: silicon-coated carbon dots (SiCDs) are used as the fluorescent group of the flexible luminescent solar concentrator (LSC) due to their large Stokes shift (150 nm) and high quantum yield (10.94%) [15]. The absorber is coated with a dark selective absorption coating on the surface of the stainless steel absorber, effectively reducing the thermal emissivity and increasing the photothermal conversion efficiency to 54.85% [4]. In terms of manufacturing processes, 3D printing technology demonstrates advantages in high-precision curved surface shaping. The arc-shaped absorber‘s composite parabolic concentrator uses this technology to manufacture the concentrator model, with the aperture width and model height reduced by 15.6% and 30.3% respectively; the solvent thermal synthesis method is used to prepare silicon-coated carbon dots (SiCDs), combined with the PDMS curing process to form a flexible LSC film (thickness 0.1 cm, energy conversion efficiency 1.05%) [13]. Additionally, the modular design optimizes the shape of the absorber using SOLIDWORKS, such as the „star“ shape absorber, which has a 7.37% improvement in light reception rate compared to the rectangular mesh structure, highlighting the direct impact of structural innovation on performance.

4. Possible Solution For Future Perspectives - Automatic Tracking Of The Sun’s Position Type Stirling Generators

4.1 Mechanical Part Design Schematic

This part of the design needs to focus on a number of issues. First, the size of the concentrator and the relative position of its two parabolic rotation surfaces. Secondly, the concentrator bracket needs to be sized appropriately, and the weight needs to be reduced by designing a hollow structure. Third, the shape of the solar panel should match with the bracket for smooth installation. Fourth, the material selection of the concentrator and the concentrator bracket.

In terms of the fixing method, as shown in Fig. 1, all the parts in this part are fixed to each other by bolts and nuts. It is worth noting that the two parabolic rotating surfaces of the concentrator need to be co-focused. As for the material selection, both the concentrator and the concentrator bracket are made of aluminum alloy, while the reflective coating is applied to the two parabolic rotating reflective surfaces of the concentrator.

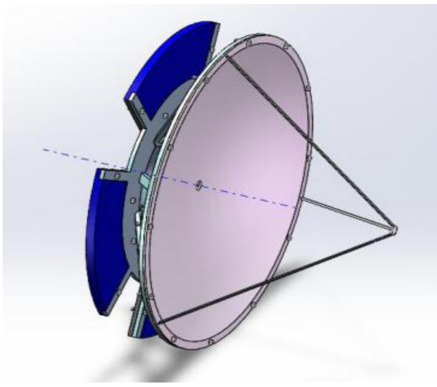

Fig. 1 Fitting of concentrator, concentrator bracket and solar panel

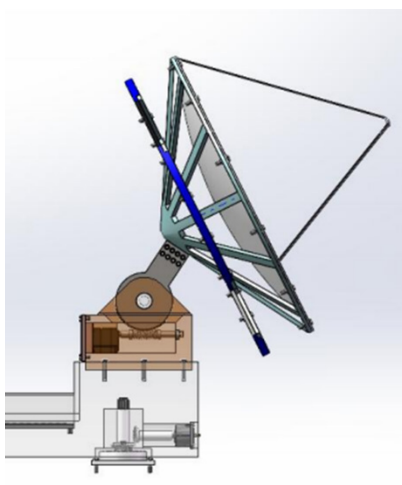

Fig. 2 Schematic diagram of elevation and horizontal turning angle adjustment

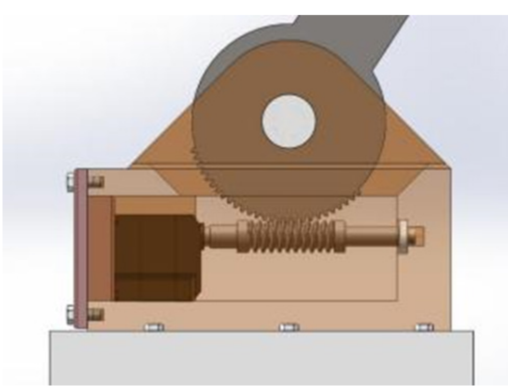

Fig. 3 Elevation adjustment connector, rotation adjustment connector, worm gear, motor (elevation adjustment)

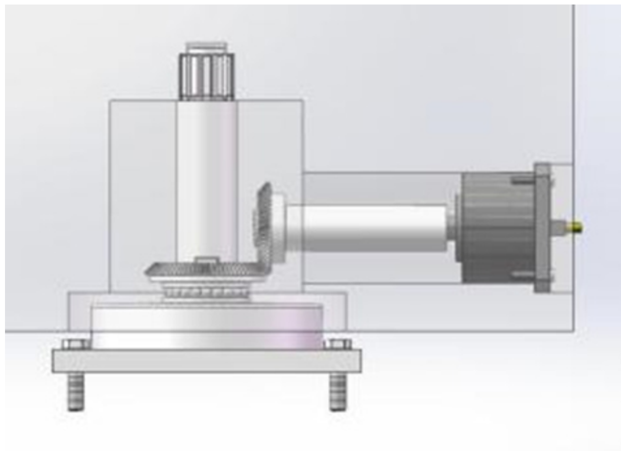

Fig. 4 Base, vertical shaft, horizontal shaft, bevel gears (two), thrust ball bearings, motor (horizontal rotation adjustment)

Fig 2 shows the elevation angle and horizontal angle adjustment schematic diagram, Fig 3 and Fig 4 for the corresponding local elevation angle adjustment mechanism and horizontal angle adjustment mechanism schematic diagram.

The design of this part mainly considers two key issues, one is the size of each part and its relative position, and the other is the choice of materials for each part. In view of the rotary adjusting link and worm gear running speed is very low and will not continue to run, so in the choice of materials, can be considered to use gray cast iron HT200 to manufacture.

The rotary adjusting link is made of engineering plastics.

Vertical shaft, horizontal shaft and bevel gear due to low speed and not continuous operation, so the two shafts using ordinary carbon structural steel Q235, bevel gear using gray cast iron HT200.

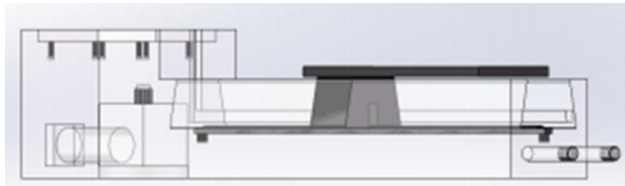

Fig. 5 Interfacing of slider rack and pinion guides

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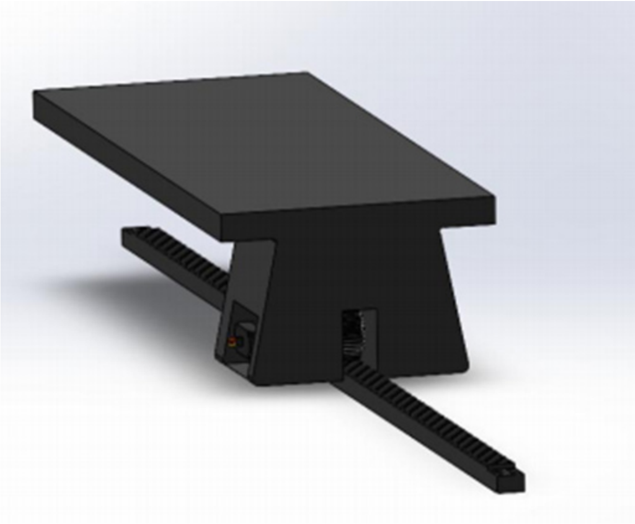

Fig. 6 Interfacing of slider, rack and pinion, gear shaft, and motor

Fig 5 is a schematic diagram of the structure of the slider and the rack and pinion guide. As shown in Fig 6, after the rack and pinion is fixed on the guide rail, the gears on the slider and the rack and pinion cooperate with each other, and the slider is assembled with a gear shaft and a motor inside the slider, and the gears cooperate with the rack and pinion to drive the slider to move along the guide rail.

This part of the design mainly focuses on four key aspects to consider. The first is the lubrication between the guide and the slider to ensure its good operation. Secondly, the size and relative position of each part to ensure the accuracy of the installation and coordination of parts. Then is the choice of materials for each part to meet the performance requirements. Finally, it is also necessary to consider the wiring of the motor to ensure the normal operation of the motor.

The relative motion between the guide rail and the slider is slow, so consider using grease lubrication, which can provide better lubrication in low-speed movement and reduce friction and wear.

The relative motion of the gear shaft and rack is slow, so both materials are considered gray cast iron HT200. guide rail in order to have good support, can be considered using ordinary carbon structural steel Q235.

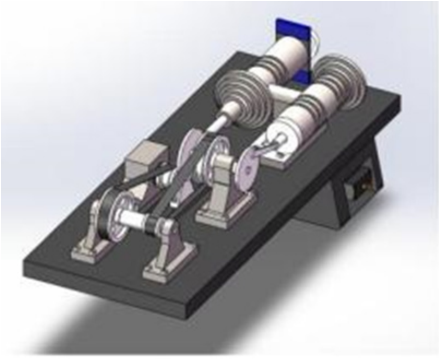

Fig. 7 Schematic diagram of the Stirling generator on the slider (1)

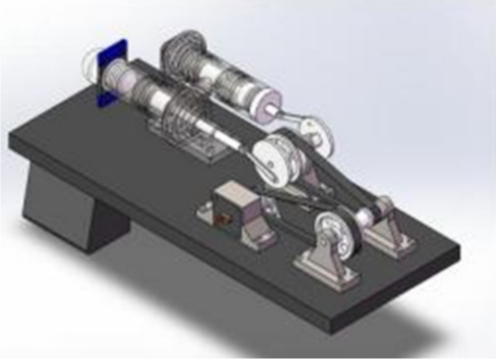

Fig. 8 Schematic diagram of the Stirling generator on the slider (2)

As shown in the fig 7 and fig 8 above, the Stirling generator part is fixed on the slider. The design of this part is centered on three important aspects. First, the lubrication of the part is taken care of to ensure its smooth operation. Secondly, the dimensions of the parts are carefully determined to ensure a precise fit between the parts. Third, the materials used for each part are carefully selected to meet performance and functional requirements. Since the running speed is not high, grease lubrication can be used.

4.2 Working Principle

Stirling generator by means of the temperature difference between the cylinder gas in the hot and cold working ends, through the closed cycle of cooling, compression, heating and expansion to push the piston to do external work. It contains two cylinder-piston systems corresponding to high-temperature heat absorption and low-temperature heat release respectively, and the work gas is connected between the two cylinders by a heat storage type return heater, and the cycle covers the stages of isothermal compression and heat release, isovolumic heat absorption, isothermal expansion and heat absorption, and so on. The concentrator gathers light beams and shoots them to the collector, so that the light energy is converted into heat energy and transferred to the Stirling generator, thus realizing the conversion of heat energy to mechanical energy and then to electric energy.

When tracking the position of the sun, the device drives the motor forward and reverse through the voltage difference generated by a pair of solar panels due to the difference in the received light signals, so as to realize the movement and direction adjustment of the device. There are three sets of adjustments and their division of labor is clear. The upper and lower solar panels on the concentrator bracket adjust the concentrator elevation angle, the left and right solar panels regulate the rotation of the device on the base, and the two solar panels on the collector are used to regulate the movement of the slider to ensure that the gathered beam continues to irradiate the collector.

5. Conclusion

The synergistic design of composite curved solar concentrator and tracking mechanism shows significant potential in enhancing solar energy utilization efficiency. Studies have shown that through two-stage concentrating technology, absorber structure optimization and intelligent tracking strategy, the system concentrating efficiency and heat flow uniformity have been effectively improved, while the tracking-free design reduces the application cost through structural innovation. However, the current research still faces the challenges of insufficient material weathering, limited adaptability to complex environments and high cost of high-precision tracking system. In the future, it is necessary to further explore the multi-material composite design to enhance environmental tolerance, develop intelligent adaptive tracking algorithms, and promote the integrated application of light-heat-electricity-storage multi-energy cogeneration technology. In addition, the potential of modular concentrators in space energy networks needs to be explored to provide new ideas for building a sustainable energy system.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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