Design and Performance Study of Triple Reflection Solar Concentrated Photocatalytic Nitrate Reduction Reactor

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Introduction

Nitrate, as a common pollutant in surface water pollution, has become a hot research topic on how to effectively remove or convert it into valuable ammonia salts [1, 2]. While nitrate's high solubility complicates its removal, methods such as ion exchange, reverse osmosis, electrochemical catalysis, and biocatalytic oxidation have been explored [3-5]. However, these approaches face limitations, including high costs, energy demands, and limited adaptability. Photocatalysis has thus gained attention as a sustainable alternative, offering operational simplicity, cost-effectiveness, and the direct utilization of solar energy, making it a promising solution for nitrate pollution remediation. Photocatalysis research primarily focuses on two key areas: advanced photocatalyst development and photocatalytic reactor optimization. In photocatalyst design, the goal is to create materials with strong light responsiveness, high stability, and cost efficiency. TiO_2 has become a leading candidate due to its stability, low cost, and widespread use as a photocatalyst substrate [6-8].

Although significant research has been conducted on photocatalytic nitrate reduction, challenges such as narrow light-responsive bandwidth and low optical efficiency due to the reflective properties of photocatalytic materials remain unresolved. To address these issues, we propose a novel approach involving the doping of titanium dioxide (TiO_2) with various atoms and co-loading them onto a substrate. Furthermore, we integrate this modified TiO_2 with a triple-reflection concentrator featuring a quasi-integrating sphere structure. This design not only broadens the light-responsive spectrum but also enables multiple absorption and utilization of reflected light, thereby ensuring enhanced optical efficiency of the system.

Construction of the system

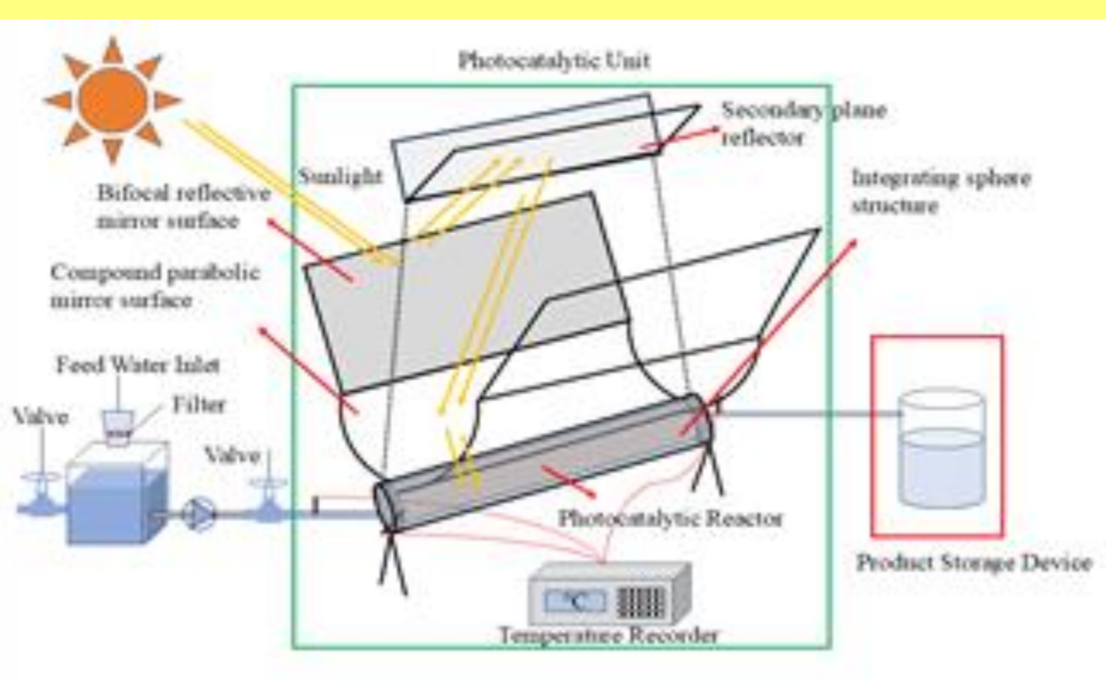


Fig.1 Schematic diagram of flat plate photocatalytic nitrate reduction system

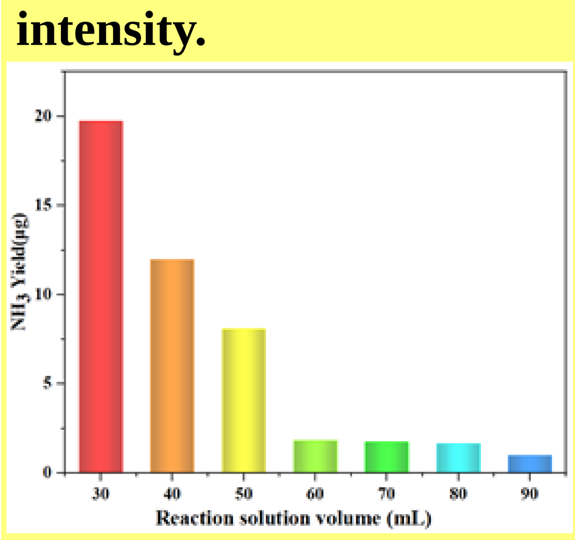
As Shown in the Fig.1, the solar photocatalytic nitrate reduction system consists of a bifocal reflective mirror, a secondary planar reflector, an integrating sphere structure, a compound parabolic concentrator, a temperature probe, and a paperless recorder. Auxiliary components, including a raw water storage tank and a water pump, further support the system. Incident light is first reflected by the primary mirror onto the secondary planar reflector, which then redirects it to form a compound parabolic surface. This design ensures efficient light capture, as peripheral rays from the integrating sphere-like structure are reflected inward. Unlike non-concentrating systems—where light reflection drastically diminishes photocatalytic efficiency—the condensed light within the integrating sphere undergoes multiple internal reflections, significantly improving photon absorption and overall system efficacy.

Experiment

3.1 Photocatalytic performance test

Light intensity, reaction temperature, reaction volume, and catalyst ratio are the primary factors influencing photocatalytic performance. Since reaction temperature is closely linked to light intensity and reaction volume, we designed controlled experiments to systematically evaluate their effects. The findings provide critical data for photocatalytic reactor optimization.

3.1.1 Photocatalytic performance test of different reaction liquid volumes under the same light intensity.



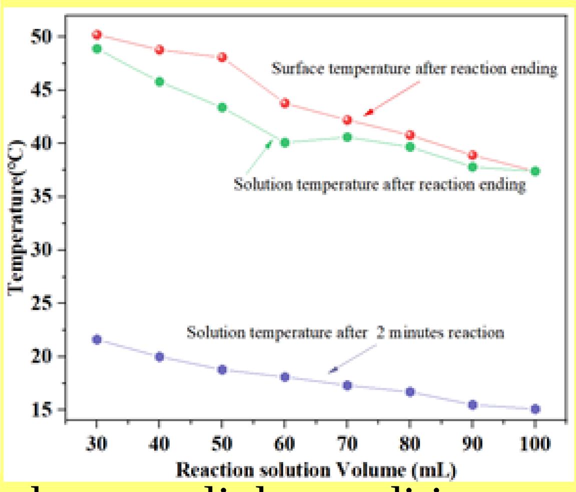
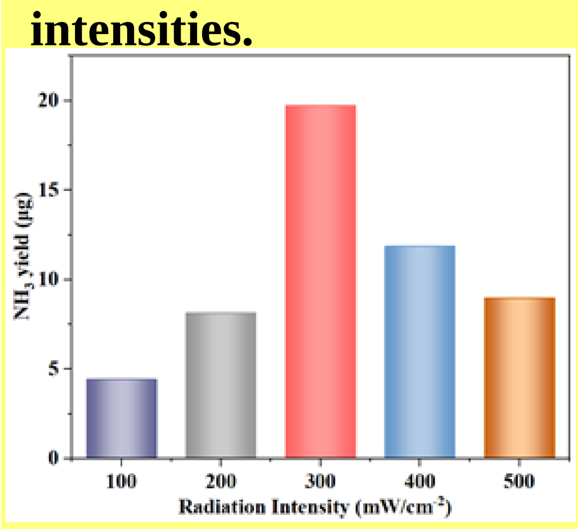


Fig.2. ammonia yield under the same light conditions, Fig.3. reaction interface and reaction solution temperature under the same light conditions

At a fixed light intensity of 300 mW/cm², we investigated the relationship between reaction interface temperature, solution temperature, and nitrate-to-ammonia conversion. Results indicate that as reaction volume increases, photocatalytic yield declines (Fig. 2). Fig.3 further reveals that both the reaction interface temperature and maximum solution temperature decrease with larger volumes. This is attributed to reduced average light intensity within the solution, lowering photothermal conversion efficiency. Additionally, diminished photothermal effects weaken the reaction's synergistic enhancement, ultimately decreasing ammonia production.

3.1.2 Photocatalytic performance test of the same volume of reaction solution under different light intensities.



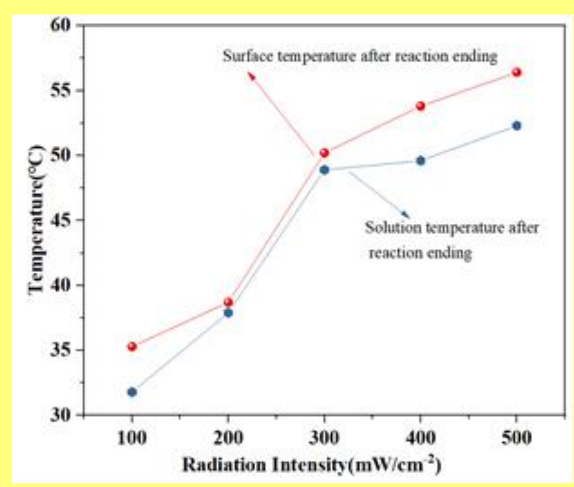
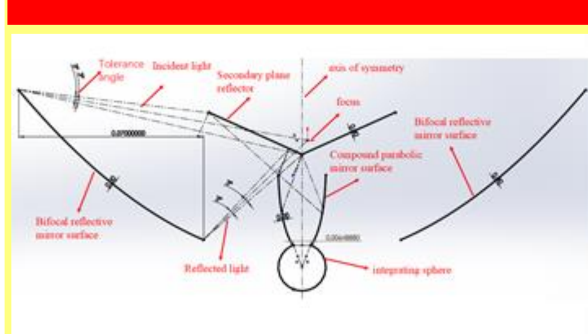


Fig.4 ammonia yield under the different light conditions, Fig.5 reaction interface and reaction solution temperature under the different light conditions

To identify optimal conditions, tests were conducted at different light intensities while maintaining a fixed reaction volume. As shown in Fig.4, ammonia yield initially rises but declines beyond a threshold, suggesting excessive light intensity may impair catalyst activity. Nevertheless, higher intensities generally outperform lower ones in terms of yield. Fig.5 further confirms that elevated temperatures positively influence ammonia production.

Optical Design



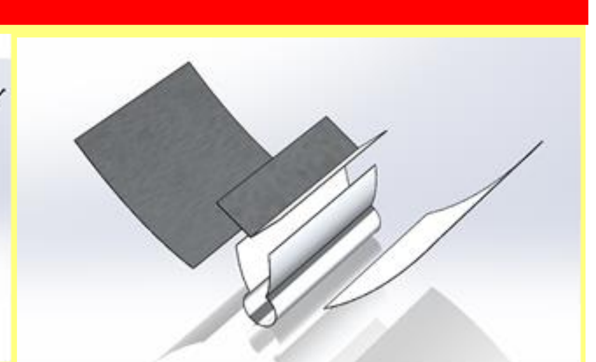
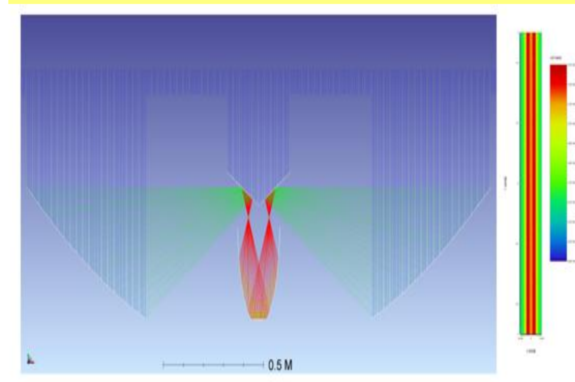


Fig.6 Structure diagram of triple reflection concentrator
Fig.7 Model diagram of triple reflection concentrator

As shown in Fig.6 and Fig.7, the three-stage concentrating photocatalytic reactor is designed with a 3° positive and negative tolerance to ensure that the plane plate can accept the light with a 3° tolerance.



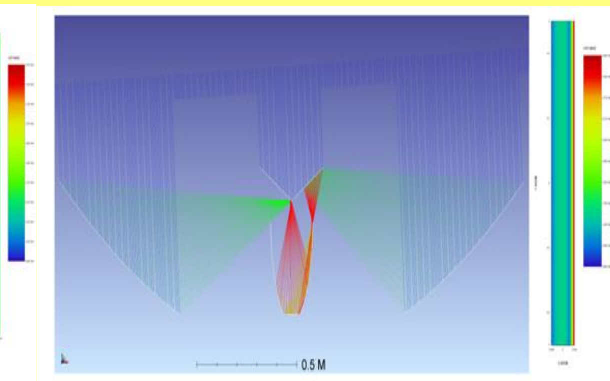
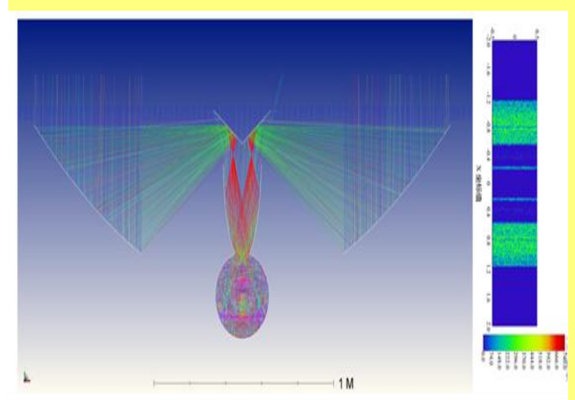


Fig.8. Optical simulation of a class-free integrating sphere structure at 0° incidence angle; Fig.9. Optical simulation of a class-free integrating sphere structure at 3° incidence angle



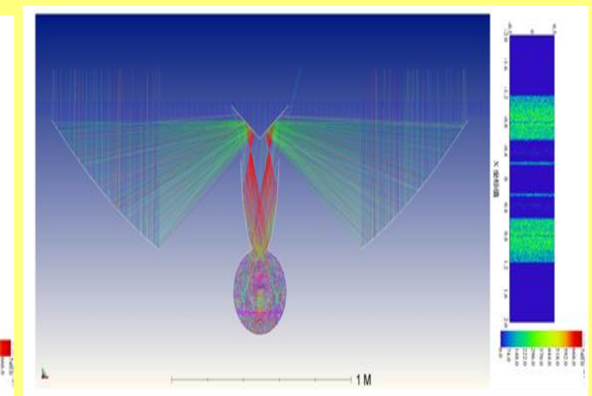


Fig.10. Optical simulation of integrating sphere like structure with 0° incidence angle; Fig.11. Optical simulation of integrating sphere like structure with 3° incidence angle

After defining the structure of the concentrating photocatalytic reactor, it is necessary to conduct optical simulation to ensure that it meets the design requirements. Set the solar irradiance as 1200 W/m^{-2}, the reflectivity of the reflecting mirror as 98%, the receiving surface area as 0.08 m^2, the incident area as 1.2 m^2, and the designed geometric concentrating ratio as 15. The simulation results show that (Fig. 8 to Fig. 11), when the integrating sphere like structure is not included, the irradiance corresponding to 0-degree incidence is 17996.25 W/m^{-2}, and the irradiance corresponding to 3-degree incidence is 16933.75 W/m^{-2}, and the corresponding energy flow concentration ratio is 14.996 and 14.115, respectively. When the integrating sphere structure is included and the reflectivity of integrating sphere is set at 50%, the irradiation power of 0° and 3° loss is 229.6 w and 200.73 w, respectively, and the corresponding relative optical efficiency is 84.05% and 86.04%, respectively. The above simulation results show that the structural design meets the design purpose and has a good focusing effect.

Conclusions

The main conclusions drawn from all these work are:

- The study identifies light intensity, reaction volume, and catalyst ratio as critical factors affecting nitrate-to-ammonia conversion. An optimal slurry ratio of 4:1 maximizes yield, while excessive light intensity or catalyst loading reduces efficiency due to active site blockage or thermal imbalance.
- The novel reactor achieves efficient light trapping via a ±3° optical tolerance, compound parabolic grooves, and an integrating sphere structure. Simulations confirm 84–86% optical efficiency even at oblique incidence (3°), demonstrating robust concentration.
- Higher temperatures enhance ammonia production, but their dependence on light intensity and reaction volume necessitates balanced design. Declining photothermal conversion at larger volumes directly correlates with reduced yields.

References

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