

Article

Study on the Sustainable Degradation of Sulfur Hexafluoride by Thermal Plasma for Greenhouse Gas Abatement

Shan Zhu ¹, Yue Zhao ¹, Haoxin Hu ², Fengxiang Ma ¹, Jun Cao ¹, Tao Lin ¹, Jiachen Li ² and Xianhui Chen ^{2,*} 

¹ State Grid Anhui Electric Power Research Institute, Hefei 230601, China; shanzhudk@163.com (S.Z.); yzhao84@163.com (Y.Z.); njumfx@foxmail.com (F.M.); caoj0533@163.com (J.C.); lintao@ustc.edu.cn (T.L.)

² Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230601, China; hhx@ustc.edu.cn (H.H.); acehijln@mail.ustc.edu.cn (J.L.)

* Correspondence: chenxian@ustc.edu.cn

Abstract

This study addresses the challenges of efficiency and cost in traditional sulfur hexafluoride (SF₆) degradation methods and the throughput limitations of common plasma technologies, with the aim of promoting sustainable treatment of potent greenhouse gases. A method of premixing SF₆ with plasma media before entering the plasma discharge region was employed to systematically investigate the effects of three atmospheres—nitrogen, air, and hydrogen—on the degradation efficiency, product distribution, and energy efficiency of SF₆. An experimental setup was constructed, and Gibbs free energy minimization simulations were conducted to analyze the degradation performance under different conditions. The results show that the premixed gas injection method achieves a degradation removal efficiency of over 99.84% when the SF₆ flow rate is lower than 4 slm, which is significantly better than the staged mixing method. When the discharge current increases from 40 A to 100 A, the degradation effect of SF₆ improves significantly, but the improvement becomes marginal when the current is further increased to 120 A. Compared with nitrogen, air and hydrogen atmospheres can effectively enhance the degradation removal rate, with the air atmosphere achieving the highest energy yield of 271 g/kWh. This research reveals the regulatory mechanism of medium components on SF₆ degradation, providing a theoretical basis for the sustainable, full-process treatment of industrial-scale reactors and contributing to the mitigation of greenhouse gas emissions.

Keywords: sulfur hexafluoride (SF₆); thermal plasma degradation; greenhouse gas abatement; sustainable waste gas treatment; chemical equilibrium analysis; industrial-scale treatment



Academic Editor: Matthew Jones

Received: 15 September 2025

Revised: 2 November 2025

Accepted: 3 November 2025

Published: 10 November 2025

Citation: Zhu, S.; Zhao, Y.; Hu, H.; Ma, F.; Cao, J.; Lin, T.; Li, J.; Chen, X. Study on the Sustainable Degradation of Sulfur Hexafluoride by Thermal Plasma for Greenhouse Gas Abatement. *Sustainability* **2025**, *17*, 10030. <https://doi.org/10.3390/su172210030>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Sulfur hexafluoride (SF₆), with its excellent insulating properties and chemical stability, plays an indispensable role in fields such as gas-insulated switchgear in the power industry and plasma etching in semiconductor manufacturing [1]. The global warming potential (GWP) of SF₆ is as high as 25,900. This means that emitting 1 kg of SF₆ generates the same greenhouse effect as emitting 25,900 kg of carbon dioxide. It is one of the greenhouse gases with the highest GWP value and has thus been listed as a key-controlled greenhouse gas in the Kyoto Protocol of the United Nations Framework Convention on Climate Change and the Paris Agreement. From 1994 to 2020, the concentration of SF₆ in the global atmosphere surged from 3.67 ppt to 10.5 ppt [2]. With the increasing global attention to climate change issues, effectively controlling SF₆ emissions has become an urgent task.

However, traditional degradation methods are mired in the dilemma of efficiency and cost. Thermal catalytic degradation requires the use of catalysts such as CePO_4 and activates the reaction at temperatures above 800°C . Although the degradation rate can be increased to 85% [3], the catalyst activity declines due to the phase transition of the support of the high-temperature catalyst, $\gamma\text{-Al}_2\text{O}_3$ to $\alpha\text{-Al}_2\text{O}_3$. Moreover, for every 1 kg of SF_6 treated, 0.5 kg of lime is consumed to adsorb by-products. Photocatalytic degradation can achieve a degradation rate of 60% by using ultraviolet excitation on the surface of polyisoprene [4]. However, the 4 h treatment duration and a single-batch processing capacity of 50 L fall considerably short of satisfying the annual demand within the power industry, which requires the treatment of tens of thousands of metric tons of waste gases.

Common plasma technologies used for the degradation of sulfur hexafluoride include radio-frequency plasma [5,6], microwave plasma [7,8], dielectric barrier discharge [9,10], etc. These plasma sources exhibit distinct generation methods and reaction activities, yet all of them fall within the category of non-thermal plasmas where the electron temperature significantly exceeds that of heavy particles. Non-thermal plasmas exhibit significant potential in laboratory settings. For instance, microwave plasma can achieve a degradation rate of 99.9% for 2.4% SF_6 at a power of 6 kW, and radio-frequency plasma can reach a degradation efficiency of 99.87% at a power of 50 W. However, due to their non-equilibrium characteristics and discharge power scales that are typically only in the tens to hundreds of watts, the treatment volume rarely exceeds 1 L/min. This makes it challenging to overcome the throughput limit, significantly impeding the transition of this technology to industrial applications.

Thermal plasma possesses unique advantages, including a local temperature exceeding 3000 K and a state of thermodynamic equilibrium. At these high temperatures, SF_6 molecules can be entirely dissociated into their constituent S and F atoms. By introducing reactive gases like nitrogen (N_2), hydrogen (H_2), water vapor (H_2O), or oxygen (O_2), the recombination of sulfur-fluorine (S-F) atoms can be effectively suppressed. The resulting products, including sulfuryl fluoride (SOF_2), thionyl tetrafluoride (SOF_4), sulfuryl difluoride (SO_2F_2), and hydrogen fluoride (HF), are acidic gases that are readily absorbed by alkaline solutions. Compared to non-thermal plasma degradation methods, the treatment volume of thermal plasma degradation methods has increased by more than an order of magnitude [11]. Ding and Sun investigated the impact of parameters such as reaction temperature, the mixing ratio of hydrogen or oxygen, and discharge power on the degradation of SF_6 through chemical kinetic simulations and experimental tests [11,12]. Under optimal conditions, the degradation removal efficiency (DRE) of SF_6 can reach 99%, and the energy yield can reach 206 g/kWh. However, in their study, the plasma working gas contained a significant amount of argon to stabilize plasma combustion, which led to increased costs for the carrier gas. Moreover, the engineering challenge of sulfur adhering to the reaction chamber, which is difficult to remove, is not favorable for direct engineering applications. The plasma wet scrubber, utilized for the treatment of perfluorinated compound (PFC) waste gas in the semiconductor industry [13], employs nitrogen plasma to mix with highly diluted (concentration $\leq 1\%$) perfluorinated compounds (PFCs) for degradation. It does not directly utilize plasma and still cannot achieve high-throughput degradation of SF_6 .

In response to the aforementioned research gaps, the novelty of this study lies in employing a method that premixes SF_6 with plasma media prior to its entry into the plasma discharge region, which is distinctly different from the downstream staged-mixing methods commonly reported in the literature. This method capitalizes on the high temperature, high enthalpy, and high chemical reactivity of thermal plasma to enhance the treatment concentration, treatment volume, and degradation rate of SF_6 . The paper systematically compares the influence of three atmospheres—nitrogen (neutral environment), air (oxidizing

environment), and hydrogen (reducing environment)-on the degradation efficiency (DRE), product distribution, and energy efficiency (EY) of SF₆. By combining Gibbs free energy minimization simulations, the regulatory mechanism of medium components on SF₆ degradation is deeply elucidated, offering a robust theoretical foundation for the full-process treatment of industrial-scale reactors.

2. Experimental Setup and Evaluation Method

2.1. Experimental Setup

This experiment aims to investigate the degradation effect of thermal plasma on SF₆ when using nitrogen, air, and hydrogen as the plasma working gases. The experimental setup as shown Figure 1, mainly consists of a power supply, gas supply, a plasma generator, a reaction chamber, a gas absorption system (including spaying, washing and absorption). The power supply first applies an over-voltage between the cathode and the arc-starting anode to start the arc, and then maintains a stable current between the cathode and the main-arc anode to ensure the continuous generation of thermal plasma. The gas supply accurately regulates the flow rates of SF₆ and plasma media (air, nitrogen, and hydrogen) through mass flow meters. There are two intake methods: one involves pre-mixing SF₆ with the plasma media before entering the plasma generator, while the second method entails introducing SF₆ in stages through a second intake port into the plasma generator. The plasma generator is the core component, adopting a DC axial-type design with a double-anode structure. There is an additional inlet between the anodes. The tangential gas-inlet method allows gas to enter the torch body with both axial and tangential velocities. This prolongs the arc length, reduces local electrode ablation, and makes the arc temperature distribution more uniform, creating conditions for the efficient degradation of SF₆. After the mixed gas enters the reaction chamber, under the action of high-temperature thermal plasma, SF₆ molecules begin to decompose. The decomposition products enter the absorption and treatment system with the gas flow. The alkaline solution tower sprays sodium hydroxide (10% NaOH) solution to absorb most of the acidic gases generated during the degradation process. Then, activated alumina and 3X molecular sieves are used to absorb gases that do not hydrolyze and do not react with the alkaline solution, such as SOF₂ and SO₂F₂.

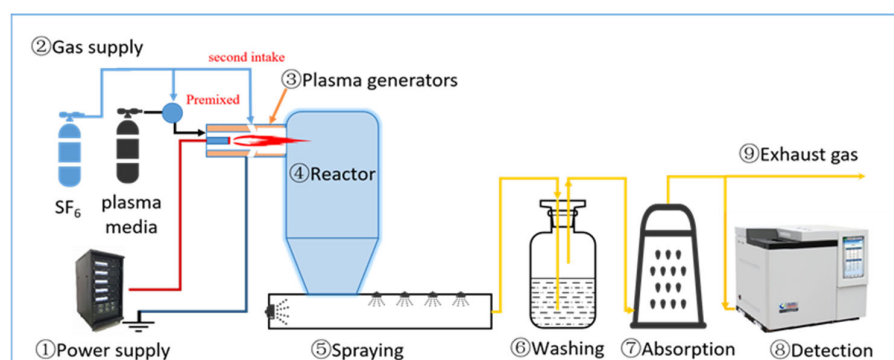


Figure 1. Schematic diagram of the experimental setup.

2.2. Evaluation Indexes

To accurately evaluate the degradation effect of SF₆ under different gas conditions, two key evaluation indexes, degradation removal efficiency (DRE) and energy yield (EY), are introduced. The degradation removal efficiency (DRE) is used to measure the degradation degree of SF₆, and its calculation formula is:

$$\text{DRE}(\%) = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (1)$$

where C_{in} is the input concentration of SF_6 before the reaction, and C_{out} is the output concentration of SF_6 after the reaction. The higher the DRE value, the better the degradation effect. The energy yield (EY) reflects the energy utilization efficiency of the degradation process, and its calculation formula is:

$$EY(g/kWh) = \frac{\dot{m}_{sf6}}{P_{plas}} \quad (2)$$

In the equation, $\dot{m}_{sf6}$ is the mass flow rate of SF_6 degraded in the reaction, and P_{plas} is the input power of the plasma. A higher EY (Energy Yield) value indicates a more efficient use of energy for SF_6 degradation.

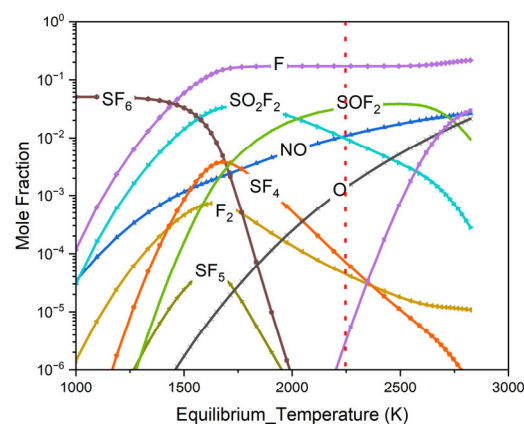
2.3. Analysis of Gas Degradation Products

In this work, a Panna Instrument A91-AMD10 Pro gas chromatography-mass spectrometry (GC-MS) instrument was used to analyze the degradation products under different gas conditions. When air is used as the plasma working gas, the degradation product components are complex. In addition to some unreacted SF_6 , a variety of sulfur-oxygen-fluorine compounds are generated, such as sulfuryl fluoride (SO_2F_2), thionyl fluoride (SOF_2), and sulfur dioxide (SO_2). This is because SF_6 reacts with oxygen and nitrogen in the air, producing a variety of oxidation products. When nitrogen is used as the plasma working gas, the degradation products are mainly a mixture of sulfur-fluorine compounds, and some sulfur-fluorine compounds will also be formed with the OH of water vapor during the water-washing process. When hydrogen is used as the plasma working gas, the degradation products are mainly hydrofluoric acid and sulfur. After being washed and absorbed by the alkaline solution, by analyzing the retention time, peak intensity, and other information of each product peak in the gas chromatogram, the types and relative contents of different products can be determined, and thus the degradation degree of SF_6 under different plasma medium conditions can be deeply understood. The results of mass spectrometry detection contain multiple substances, and potential components include SF_4 , OF_2 , SOF_4 , SOF_2 , SO_2F_2 , SO_2 , etc. The Figures S1–S3 show the detection results from the Panna A91-AMD10 Pro GC-MS, with SF_6 appearing at approximately 1.64. To further verify the accuracy of SF_6 content in exhaust gases, the Panna GC-4100-FPD method was also tested as shown in Figures S4–S6.

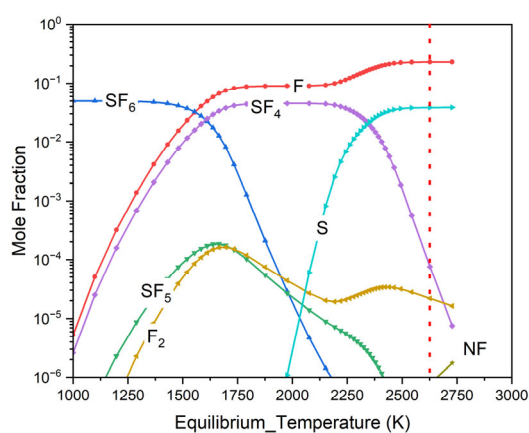
3. Results and Discussion

3.1. Chemical Equilibrium Calculation and Analysis Under Different Plasma Working Gas Atmospheres

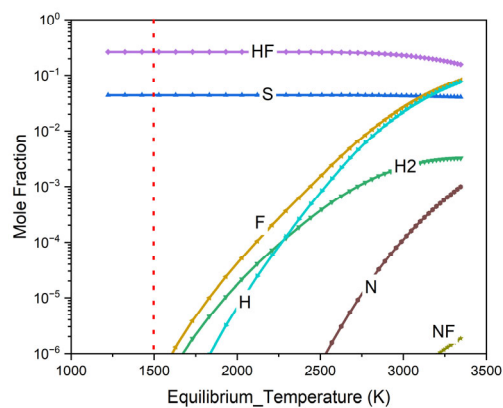
Figure 2 shows the equilibrium amounts of various substances at different reaction temperatures in systems of nitrogen (neutral environment), air (oxidizing environment), and hydrogen (reducing environment) mixed with 5% SF_6 under a 1-atm working condition. The chemical equilibrium composition was calculated using the Gibbs free energy minimization module within the ChemKin-Pro 3.0 software package. The main calculation parameters were as follows: Pressure: 1 atmosphere; Temperature Range: 500 K to 4000 K, in increments of 100 K; Considered Species: neutral molecules, atoms, and radicals (e.g., SF_6 , SF_4 , SF_2 , S, F, S_2 , F_2 , SO_2 , SOF_2 , SO_2F_2 , HF, H, H_2 , O, O_2 , N_2 , NF). Electrons and ionized particles were neglected. Only neutral molecules, atoms, and radicals were considered in the reaction components, and electrons and ionized-state particles were ignored.



(a)



(b)



(c)

Figure 2. Chemical equilibrium product distribution in various plasma working gas environments. (a) Chemical equilibrium product distribution of 95%N₂ + 5%SF₆; (b) Chemical equilibrium product distribution of 95%Air + 5%SF₆; (c) Chemical equilibrium product distribution of 80%N₂ + 15%H₂ + 5%SF₆.

When nitrogen is used as the working gas, it can be found that SF₆ molecules begin to decompose at around 1000 K. First, they lose F to form SF₅, SF₄, and F atoms. As the arc temperature rises, elemental S begins to form at around 2000 K. Overall, the temperatures required for the formation of SF₅, SF₄, and S gradually increase, and the maximum molar fraction of SF₄ is significantly greater than that of SF₅. The main reason is

that the decomposition process of SF_6 is a process in which S-F bonds are gradually broken to form low-energy-level and low-fluorine sulfides, and the bond energy of SF_4 is higher than that of SF_5 . When the arc temperature is higher than 2250 K, the molar fractions of all sulfur fluorides begin to decrease, and the decomposition products are mainly S and F atoms. However, when the temperature exceeds 2600 K, nitrogen molecules begin to be activated and dissociated, forming NF molecules. NF molecules are toxic substances that are difficult to for alkaline solutions, alumina, and molecular sieves to absorb. They should be avoided as much as possible during the degradation process. It should be noted that during the arc attenuation process, the arc temperature gradually decreases. When the arc temperature drops below 1000 K, all sulfur fluorides and atoms recombine into SF_6 . The products are mainly SF_4 at temperatures below 2500 K, while at reaction temperatures higher than 2500 K under plasma working conditions, they mainly exist in the form of dissociated S and F atoms. At this time, spray-cooling and absorption with an alkaline solution can theoretically achieve a high degradation rate.

Secondly, when air is used as the working gas, SF_6 molecules also begin to decompose at around 1000 K, first forming SO_2F_2 and F atoms. As the arc temperature rises, SF_5 , SF_4 , and SOF_2 begin to form. The temperatures required for the formation of SF_5 , SF_4 , and SOF_2 gradually increase, and the maximum molar fraction of SOF_2 is significantly greater than that of SF_4 and SF_5 . Different from the nitrogen plasma, there is no S atom in the oxidation condition. When the arc temperature is higher than 2000 K, the molar fraction of SF_6 in the system can be almost ignored. In the air atmosphere, the high-temperature products are mainly SOF_2 . Since SOF_2 is easily absorbed by the alkaline solution, the reaction control temperature range needs to be guided by SOF_2 as the product. Theoretically, when air is used as the plasma medium, due to its oxidizing property, the degradation temperature can be reduced as a whole. However, during the discharge process of air plasma, high temperatures will generate NO_x , which will cause additional pollution, and nitric oxide is not easily absorbed by the alkaline solution, causing secondary pollution.

Because the mixture of hydrogen and SF_6 as the working gas is extremely likely to cause discharge instability and has an explosion risk, only the $80\%\text{N}_2 + 15\%\text{H}_2 + 5\%\text{SF}_6$ system was subjected to chemical equilibrium calculation here. Different from using nitrogen and air as plasma media, the addition of hydrogen can greatly promote the degradation of SF_6 to form HF and elemental S. As the arc temperature rises, HF will decompose into H, F atoms, and H_2 molecules. However, when the temperature exceeds 2600 K, nitrogen molecules begin to be activated and dissociated, forming NF molecules, which is not conducive to the conditions.

In summary, through the chemical equilibrium calculation and analysis of feasible reactive gases, it can be seen that the degradation product components of the H_2/SF_6 system are few, only HF and S elements. In the Air/SF_6 and N_2/SF_6 systems, the products are more complex, but they are all gases, and most of them can be absorbed by the alkaline solution. The addition of O_2 is beneficial to reducing the discharge power of the thermal plasma torch for degrading SF_6 .

3.2. Influence of Mixing Methods on the Degradation Effect of Thermal Plasma

Two gas-inlet methods were used, namely directly discharging with N_2/SF_6 premixed as the plasma medium and downstream-staged mixing of SF_6 with N_2 as the plasma. The influence of the mixing method on the degradation effect of thermal plasma was compared. The discharge current was 60 A, the nitrogen flow rate was 40 slm, and the SF_6 flow rates were set as 1, 4, 8, 12, 16, and 20 slm, respectively. The results are shown in Figure 3. The premixed gas-inlet method can enter the plasma discharge region, which is different from the staged-mixing method. It can give full play to the energy and reaction activity of thermal

plasma. Therefore, when the SF₆ flow rate is lower than 4 slm, the degradation removal efficiency (DRE) of premixed SF₆ exceeds 99.84%. However, the staged-inlet method is difficult to maintain the degradation of relatively high-concentration SF₆. Only when the low-throughput SF₆ is 1 slm, its degradation removal efficiency (DRE) reaches 99.77%. As the SF₆ flow rate increases, the DRE values of both the premixed and staged-inlet methods will decrease significantly, but the premixed method always shows better degradation performance than the staged-mixing method. During the experiment, it was found that an increase in the SF₆ concentration can also lead to discharge instability, which has become one of the technical problems restricting the degradation of high-concentration SF₆.

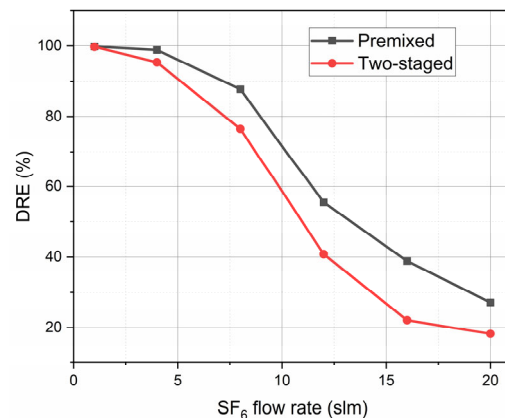


Figure 3. Distribution of degradation and removal efficiency at different SF₆ flow rates under a discharge current of 60 A.

3.3. Influence of Discharge Current on the Degradation Effect of Thermal Plasma

In order to compare the influence of the reaction temperature on the performance of thermal plasma in degrading SF₆, experimental analysis was carried out by changing the discharge current and adjusting the enthalpy value of the plasma. The premixed gas inlet mode was adopted, with the nitrogen flow rate being 40 slm, the SF₆ flow rate being 8 slm, and the discharge current set at 40~120 A. The results are shown in Figure 4. The discharge power increases with the rise in the discharge current, and the slope of the power increase is less than 1, which indicates that the arc exhibits a falling volt-ampere characteristic under this working condition. When the discharge current is lower than 40 A, the reaction temperature at the edge of the thermal plasma is not sufficient to fully degrade SF₆, resulting in a DRE of only 50.39%. When the discharge current increases from 40 A to 100 A, the degradation effect of SF₆ is significantly improved. By increasing the discharge power, the particle collisions will become more intense, and the temperature of heavy particles will also rise, which is conducive to promoting the decomposition of SF₆. When the discharge current is further increased to 120 A, the improvement of the degradation effect is relatively slight, and the DRE value only increases from 98.21% to 99.24%. This is similar to the trend of the simulation results: when the reaction temperature rises to a relatively high value, the degradation products no longer change, and further increasing the discharge power cannot improve the degradation effect.

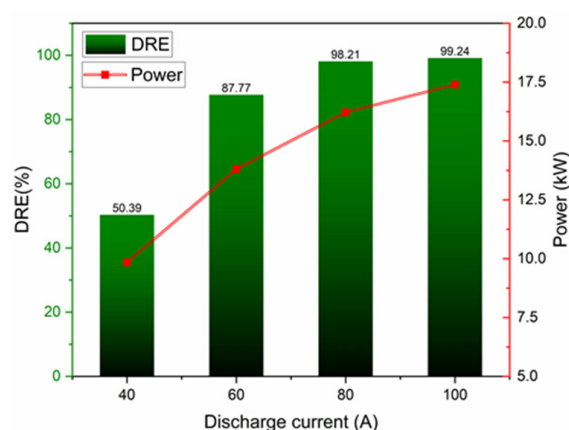


Figure 4. Distribution of Discharge Power and Degradation Removal Efficiency at Different Discharge Currents under an SF_6 Flow Rate of 8 slm.

3.4. Influence of Different Atmospheres on the Degradation Effect of Thermal Plasma

This study explores the influence of different atmospheres, including nitrogen (neutral environment), air (oxidizing environment), and hydrogen (reducing environment), on the performance of degrading SF_6 . The discharge current is set at 60 A, and the flow rates of the plasma working gases N_2 and Air are both 40 slm, respectively. Since hydrogen is likely to cause discharge instability, when studying the hydrogen reducing environment, the plasma gas is set as a mixture of 12 slm H_2 + 28 slm N_2 to ensure the good operation of the device. The results are shown in Figure 5. Compared with the neutral environment of nitrogen, both the oxidizing environment of air and the reducing environment of hydrogen can improve the degradation removal rate of SF_6 . This is consistent with the result analysis of chemical equilibrium calculations. The active gases H and O are more likely to combine with the dissociated S and F of SF_6 , inhibiting the recombination of SF_6 . Therefore, under the condition of a higher SF_6 flow rate of 8 slm, both the oxidizing environment of air and the reducing environment of hydrogen still have a degradation removal rate of over 96%, and the reducing environment of hydrogen is slightly higher than that of air, with the DRE reaching 98.13%. However, as the SF_6 flow rate continues to increase, the oxidizing environment of air shows a higher degradation removal rate than the reducing environment of hydrogen. The volume ratio of O_2 in air is approximately 21%, which is lower than the volume ratio of H_2 (30%) in the set hydrogen reducing environment. But the results of chemical equilibrium calculations indicate that the main product of SF_6 degradation by air plasma is SOF_2 , and the main product of SF_6 degradation by hydrogen plasma is HF. The number of F atoms fixed by one O atom is twice that fixed by one H atom. Therefore, as the SF_6 flow rate increases, the molar ratio of H_2/SF_6 in the atmosphere may decrease, and the insufficient hydrogen content cannot meet the degradation of high-throughput SF_6 . This phenomenon can be attributed to the different roles and fluorine fixation capacities of H and O atoms. At lower SF_6 flow rates, the H_2/SF_6 molar ratio is high. Hydrogen dissociates in the plasma to form highly reactive H radicals, which efficiently scavenge fluorine atoms to form stable HF, effectively suppressing SF_6 recombination and resulting in high DRE. In contrast, at higher SF_6 flow rates, the H_2/SF_6 ratio decreases, making the hydrogen content insufficient to capture all F atoms. Oxygen from air, however, has a higher fixation capacity for fluorine, as one O atom can fix two F atoms (e.g., in SOF_2 or SO_2F_2), whereas one H atom fixes only one F atom (in HF). Therefore, the oxidative pathway becomes more effective under high SF_6 loading, maintaining a higher degradation efficiency. Under the same current and gas flow rate, the plasma discharge power mainly depends on the medium composition. The trend of the discharge power is as follows: air < nitrogen < hydrogen. Regarding the energy yield EY, in addition to being affected by

the degradation removal rate, it also depends on the discharge power. Since air not only shows excellent degradation performance for SF_6 but also has a relatively small discharge power, it exhibits the best energy yield EY among the three atmospheres, reaching up to 271 g/kWh at the highest. Although the hydrogen atmosphere also shows good SF_6 degradation performance, adding hydrogen to the plasma is likely to cause an increase in the discharge voltage and power. Therefore, its energy yield EY is not much different from that in the nitrogen atmosphere.

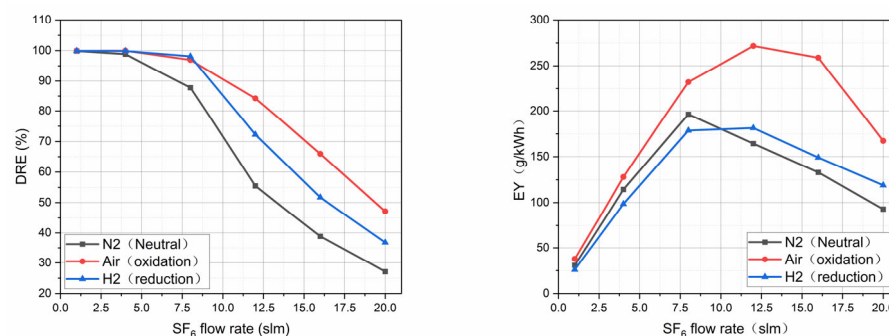


Figure 5. Dependence of degradation removal efficiency and energy yield on SF_6 flow rate under different plasma atmospheres.

Conditions: Discharge current: 60 A; Plasma gas: N_2 (40 slm), Air (40 slm), H_2/N_2 (12/28 slm); Premixed mode.

4. Summary

In this study, an experimental device consisting of an intake air control system, an arc plasma torch generator, a reaction chamber, and a gas absorption system was constructed. Two key indicators, namely the degradation and removal efficiency (DRE) and the energy yield (EY), were introduced to evaluate the degradation effect. Additionally, a gas chromatograph-mass spectrometer was used to analyze the composition of the products. On this basis, the following significant results were obtained.

Chemical equilibrium calculations show that the degradation product composition of the H_2/SF_6 system is simple. The products of the Air/SF_6 and N_2/SF_6 systems are complex, but most of them can be absorbed by the alkaline solution, and the addition of O_2 helps to reduce the discharge power. The mixing method has a significant impact on the degradation effect. The premixed air intake method gives full play to the advantages of thermal plasma. When the flow rate of SF_6 is lower than 4 slm, the degradation and removal efficiency can exceed 99.8%, which is significantly better than the staged-mixing method. The discharge current has a threshold effect on the degradation effect. It increases significantly between 40 and 100 A, but the increase is limited when it exceeds 120 A. Among different atmospheres, the air atmosphere performs best in terms of energy yield, reaching up to 271 g/kWh. The superior EY of air plasma is attributed to a combination of its effective SF_6 degradation through oxidation, the higher fluorine fixation capacity of oxygen, and critically, its lower discharge power requirement compared to nitrogen and hydrogen-mixed plasmas under identical conditions. This result indicates that when using air as the plasma working gas in the industrial-grade degradation treatment of SF_6 , there are significant advantages in reducing energy consumption costs, providing important economic feasibility reference for large-scale industrial applications.

However, there are still certain limitations in this study. Experimental findings show that a high concentration of SF_6 can lead to unstable discharge, which restricts the degradation of high-concentration SF_6 . This may be because the complex chemical reactions

triggered by the high-concentration SF₆ in the plasma environment cause the disorder of the internal electric field distribution of the plasma, thus leading to unstable discharge. In addition, the mechanisms of some side reactions during the degradation of SF₆ by thermal plasma are still unclear. This may result in the inability to effectively control the generation of by-products, thereby affecting the stability and durability of the equipment and increasing the maintenance costs and treatment difficulties in industrial applications. Future work should therefore focus on: (1) optimizing reactor geometry and power supply characteristics to mitigate discharge instability at high SF₆ concentrations; (2) employing in situ diagnostic techniques to elucidate the pathways of uncertain side reactions; and (3) scaling up the reactor design for industrial pilot testing.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su172210030/s1>, Figure S1: 4 slm-60 A-95%N₂ + 5%SF₆; Figure S2: 4 slm-60 A-95%Air + 5%SF₆; Figure S3: 4 slm-60 A-80%N₂ + 15%H₂ + 5%SF₆; Figure S4: 4 slm-60 A-95%N₂ + 5%SF₆; Figure S5: 4 slm-60 A-95%Air + 5%SF₆; Figure S6: 4 slm-60 A-80%N₂ + 15%H₂ + 5%SF₆. The Figures S1–S3 show the detection results from the Panna A91-AMD10 Pro GC-MS, with SF₆ appearing at approximately 1.64. To further verify the accuracy of SF₆ content in exhaust gases, the Panna GC-4100-FPD method was also tested as shown in Figures S4–S6.

Author Contributions: Conceptualization, S.Z. and H.H.; methodology, X.C.; software, Y.Z.; validation, F.M. and J.C.; formal analysis, T.L.; investigation, J.L.; resources, S.Z.; data curation, X.C.; writing—original draft preparation, S.Z.; writing—review and editing, X.C.; visualization, H.H.; supervision, X.C.; project administration, X.C.; funding acquisition, S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the project of State Grid Anhui Electric Power Co., Ltd. (B3120524001Q) and the National Natural Science Foundation of China (NSFC) under Grant (12475263).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the corresponding author upon reasonable request.

Conflicts of Interest: Shan Zhu, Yue Zhao, Fengxiang Ma, Jun Cao, and Tao Lin are employed by State Grid Anhui Electric Power Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. Xianhui Chen receives research grants from the project of State Grid Anhui Electric Power Co., Ltd. (B3120524001Q). The funder had the following involvement with the study: in the collection to publish the results.

References

1. Cui, Z.; Hao, P.; Yan, L.; Li, L.; Wang, Y.; Zhou, C.; Zhang, X. Review on Harmless Abatement of SF₆ Waste Gas. *Proc. CSEE* **2023**, *43*, 7720–7736.
2. Global Monitoring Laboratory. Earth System Research Laboratories. Available online: <https://gml.noaa.gov/hats/combined/SF6.html> (accessed on 15 August 2025).
3. Zhang, X.; Wang, Y.; Tian, S.; Chen, F.; Hu, J. Influence of O₂ on the Thermal Catalytic Degradation of SF₆ Waste Gas by CePO₄. *High Volt. Eng.* **2022**, *48*, 2152–2158.
4. Nanjo, Y.; Ohyama, R. An experimental study on vacuum-ultraviolet photochemical reaction to non-thermal plasma oxidized SF₆/sub 6/ gases. In Proceedings of the CEIDP '05. 2005 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Nashville, TN, USA, 16–19 October 2005.
5. Shih, M.; Lee, W.J.; Tsai, C.H.; Tsai, P.J.; Chen, C.Y. Decomposition of SF₆ in an RF Plasma Environment. *J. Air Waste Manag. Assoc.* **2002**, *52*, 1274–1280. [[CrossRef](#)] [[PubMed](#)]
6. Joshi, A.V. Decomposition of SF₆–R134a effluents by RF plasma. *Nucl. Instrum. Methods Phys. Res. Sect. Accel. Spectrom Detect. Assoc. Equip.* **2012**, *661*, S245–S248. [[CrossRef](#)]

7. Marilena, R.; Shahid, H. Microwave plasma removal of sulphur hexafluoride. *J. Hazard. Mater.* **2009**, *164*, 39–45. [[CrossRef](#)] [[PubMed](#)]
8. Kim, J.; Cho, C.; Shin, D.; Hong, Y.; Shin, Y. Abatement of fluorinated compounds using a 2.45GHz microwave plasma torch with a reverse vortex plasma reactor. *J. Hazard. Mater.* **2015**, *294*, 41–46. [[CrossRef](#)] [[PubMed](#)]
9. Cui, Z.; Zhang, X.; Yuan, T.; Xing, P.; Luo, Y.; Tang, J. Plasma-assisted abatement of SF₆ in a dielectric barrier discharge reactor: Investigation of the effect of packing materials. *J. Phys. Appl. Phys.* **2019**, *53*, 025205. [[CrossRef](#)]
10. Zhuang, Q.; Clements, B.; McFarlan, A.; Fasoyinu, Y. Decomposition of the most potent greenhouse gas (GHG) sulphur hexafluoride (SF₆) using a dielectric barrier discharge (DBD) plasma. *Can. J. Chem. Eng.* **2013**, *92*, 32–35. [[CrossRef](#)]
11. Sun, H.; Long, H.; Wu, Y.; Guo, Y.; Rong, M. Simulation and experimental study on the degradation of the greenhouse gas SF₆ by thermal plasma. *Environ. Res.* **2022**, *216*, 114411. [[CrossRef](#)]
12. Yu, D.; Hao, H.; Yun, G.; Yi, W.; Yun, Z.; Yang, L. Comparison of the Effect of H₂ and O₂ on SF₆ Degradation by Hot Plasma. In Proceedings of the 2024 7th International Conference on Electric Power Equipment-Switching Technology (ICEPE-ST), Xiamen, China, 10–13 November 2024.
13. Choi, S.-S.; Park, D.-W.; Watanabe, T. Thermal plasma decomposition of fluorinated greenhouse gases. *Nucl. Eng. Technol.* **2012**, *44*, 21–32. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.