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Review

Research Progress on Flue Gas Desulfurization and Denitrification by Activated Carbon Method

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Abstract: SO_2 and NO_x emissions from iron and steel production pollute the atmosphere. With the implementation of ultra-low emission standards, the requirements for flue gas purification have become more stringent. Activated carbon, due to its rich surface chemistry, stable physical structure, and excellent adsorption and renewability, has a significant effect on the synergistic removal of multiple pollutants from industrial flue gas, and its industrial application has achieved a SO_2 removal rate of ≥98% and a NO_x removal rate of ≥83%. Firstly, we analyze the structure of activated carbon and the adsorption principle, discuss the mechanism of desulfurization and denitrification, and explore the shortcomings of the technology; then, we summarize the modification methods of activated carbon, determine the impregnation method of loading non-precious metal oxides as the optimal solution, and elucidate the loading conditions, process, and reaction mechanism; finally, we discuss the current status of the research, analyze the process deficiencies and the direction of optimization, and look forward to the prospect of development.

Keywords: activated carbon; flue gas; microwave; non-precious metal oxides; desulfurization and denitrification

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1. Introduction

The flue gas produced by the iron and steel production process mainly contains acidic gaseous pollutants such as SO_2 and NO_x that destroy the ozone layer; cause acid rain and greenhouse effects; damage the human respiration, digestion, cardiovascular, and immune systems; and contain carcinogenic SO_2 and NO_x (Figure 1) [1–6]. The mass concentration of SO_2 emission in the flue gas of domestic iron and steel enterprises is 300–800 mg/Nm^3, and the maximum can reach 2000–4000 mg/Nm^3. The NO_x mass concentration is 0.15–0.30g/Nm^3 and can reach up to the 0.5–0.6 g/Nm^3 range [7]. Therefore, improving and optimizing the treatment capacity of pollutants such as sulfur and nitrate in flue gas plays a vital role in the green and sustainable development of the steel industry. Although the existing flue gas desulfurization and denitrification technology can meet the requirements of production and environmental protection, there are still many problems, such as the complex process, low efficiency, poor water resistance, high input and operating costs, difficult recovery and reuse of by-products, and secondary pollution [8–10].

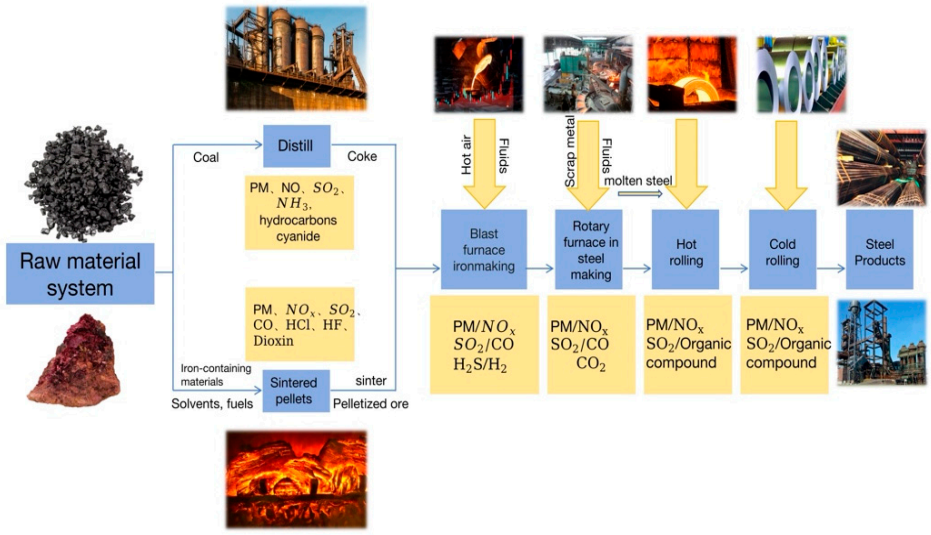


Figure 1. Pollutants produced by various processes in iron and steel production.

Among many flue gas treatment methods, activated carbon desulfurization and denitrification technology is the only way to simultaneously remove various pollutants such as sulfides, nitrogen oxides, dioxins, and heavy metals in flue gas [11]. Activated carbon flue gas desulfurization and denitrification mainly includes three technologies: 'downstream', 'cross-flow', and 'countercurrent'. Compared with the 'downstream' and 'cross-flow' technology, the 'countercurrent' technology has more advantages in adsorption kinetics. In the countercurrent technology, the reverse flow mode of activated carbon and flue gas increases the mass transfer driving force by 30% through concentration gradient optimization to ensure that the SO_2 adsorption efficiency is stable at $\geq$98.5% [12]. The axial saturation gradient of the bed reaches 0.8–1.2 kg SO_2/kg AC·m, the horizontal saturation deviation is less than 5%, and the bottom sulfur capacity can reach 400–500 mg/g (15–20% higher than that of the downstream process). This design increases the treatment capacity per unit volume to 1200–1500 $m^3/(m^2 \cdot h)$, maximizing the utilization of the adsorption capacity and optimizing energy consumption [13]. Therefore, the 'countercurrent' technology is more widely used, such as by Handan Steel [14], Anyang Steel [15], and other large iron and steel enterprises. Activated carbon desulfurization and denitrification technology has the advantages of a high desulfurization rate (close to 100%), low energy consumption, recyclable by-products, and simple process. This has been widely recognized by the academic community. However, its denitrification effect is unsatisfactory. In the actual production process, the denitrification effect can only be achieved by spraying ammonia at multiple places [16]. In addition, when activated carbon is used for simultaneous desulfurization and denitrification, SO_2 and NO_x will form a competitive adsorption at the active sites on the surface of activated carbon, affecting the desulfurization efficiency. Therefore, in order to improve the desulfurization and denitrification efficiency of activated carbon and avoid the waste of resources, research on the modification of activated carbon in the desulfurization and denitrification process of activated carbon came into being.

This review covers the process technology and the reaction mechanism of activated carbon desulfurization and denitrification. At the same time, it reviews the research results of scholars in recent years in improving the efficiency of flue gas desulfurization and denitrification by modified activated carbon. On this basis, the advantages and shortcomings of the flue gas desulfurization and denitrification process with activated carbon are highlighted.

2. Reaction Mechanism of Activated Carbon and Flue Gas Sulfur Nitrate

2.1. Activated Carbon and Its Characteristics

Activated carbon is a black porous solid carbon made of carbon-containing materials such as high-quality coal, wood chips, and fruit shells. Activated carbon is refined through a series of processes such as carbonization, cooling, activation, and washing [17]. The density is 1.8–2.1 g/cm^3, the apparent density is 0.08–0.45 g/cm^3, and the carbon content is 10–98%. Activated carbon is odorless and porous and has a strong adsorption capacity for gas or colloidal solids. The total surface area per gram of activated carbon can reach 500–1700 m^2, and the ignition point is above 300 °C. The large specific surface area and microporous structure of activated carbon provide it with unique multi-functional adsorption [18–22].

According to the different classification criteria depicted in Figure 2 and cited in References [23–27], they can be categorized according to the raw material used to make them, the state of appearance presentation, and the size of the stomata.

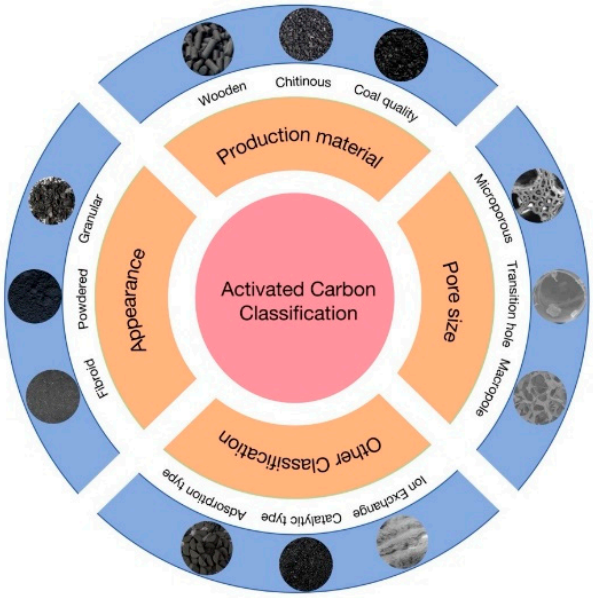


Figure 2. Different kinds of activated carbon.

Different raw materials can be divided into wooden activated carbon, shell activated carbon (coconut shell activated carbon), coal activated carbon [23], and other raw activated carbon (such as animal bone activated carbon, mineral raw activated carbon, synthetic resin activated carbon, rubber or plastic activated carbon, regenerated activated carbon, etc.). Among them, wood activated carbon, shell activated carbon, and coal activated carbon are most widely used in production and life. According to the appearance of the present form, it can be divided into powder activated carbon, granular activated carbon, and fiber activated carbon [24]. Activated carbon can also be classified according to the pore size. Dubinin, a scholar of the former Soviet Union, proposed that a pore diameter between 100 and 2000 nm is a large pore activated carbon; a pore diameter between 2 and 100 nm is mesoporous (also known as transition pore) activated carbon; and microporous activated carbon has a pore diameter of less than 2 nm [25]. The International Union of Theoretical and Applied Chemistry (IUPAC) lists macroporous activated carbon with a pore diameter above 50 nm, mesoporous activated carbon with a pore diameter between 2 and 50 nm, and microporous activated carbon with pore diameter below 2 nm [26]. In addition to the above three classifications, activated carbon can also be classified differently according to the specific use and manufacturing process [27].

2.2. Adsorption Function and Principle of Activated Carbon

The adsorption function of activated carbon is mainly affected by the pore structure, specific surface area, and functional groups, and the pore size plays a decisive role in the adsorption performance [28,29]. The pores are divided into macropores, micropores, and transition pores according to the diameter. The proportion of macropores and transition pores in activated carbon is relatively small, which plays a role in the adsorption pathway process and dominates the adsorption rate. Most of the actual adsorption is carried out in micropores, and the number of micropores plays a dominant role in the adsorption capacity (Figure 3).

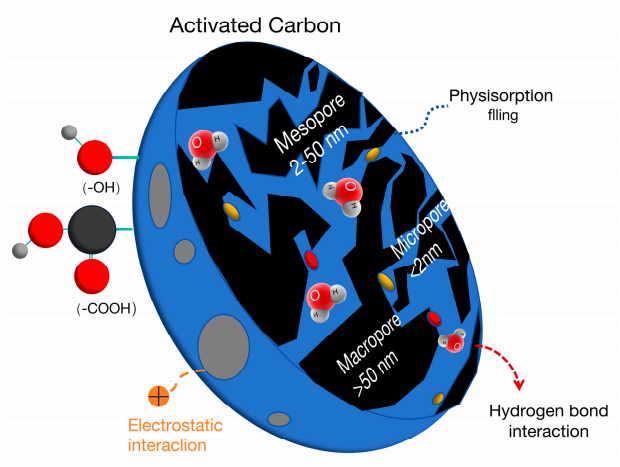


Figure 3. Pore structure and adsorption principle of activated carbon [30].

The porous structure of activated carbon provides a huge specific surface area for it. The more developed the pore structure is, the larger the specific surface area will be, and the stronger the adsorption function.

The adsorption function of activated carbon is divided into physical adsorption and chemical adsorption. The physical adsorption of activated carbon is generated by intermolecular forces, and van der Waals force is the main force [31]. Intermolecular forces are ubiquitous among all molecules. Any substance has a certain adsorption capacity, and the adsorbed molecules can also adsorb other molecules. Therefore, physical adsorption is multi-molecular layer adsorption. As adsorbents, substances can often adsorb various other substances, so physical adsorption has no selectivity. Due to the relatively weak intermolecular forces, the adsorbed substances are often easier to desorb, so the physical adsorption is reversible [32]. For chemical adsorption, the adsorbate molecules and the surface atoms of the adsorbent will undergo electron transfer, exchange, or sharing, thereby forming chemical bonds, such as covalent bonds and ionic bonds. Chemisorption has strong selectivity, that is, an adsorbent only chemically adsorbs a specific adsorbate. Chemical adsorption requires sufficient energy to overcome the activation energy of the reaction, so it is usually significant at high temperatures. In the flue gas desulfurization and denitrification of activated carbon, some functional groups on the surface of activated carbon will produce weak chemical adsorption with some adsorbates, but physical adsorption is dominant. Some scholars have studied the adsorption of SO_2 molecules on the surface of perfect graphene and vacancy defect graphene and calculated the corresponding properties of SO_2 adsorbed on perfect graphene (PG) by means of density functional theory (DFT). The results showed that the adsorption process was achieved by physical adsorption, and the adsorption energy (Eads) of different adsorption configurations ranged from −0.125 eV to −0.314 eV. In addition, it is found that the presence of vacancies can improve the sensitivity of graphene to detect SO_2 molecules and promote the strong adsorption

of surface SO_2 molecules on the surface of vacancy defect graphene. Further calculation of the electronic properties shows that there is a hybridization between the S-2p orbital of the SO_2 molecule and the C-2p orbital of the vacancy defect graphene (VG), which is the reason for the increase in the SO_2/VG adsorption energy [33]. At the same time, other scholars have studied the diffusion behavior of NO molecules in the pores of activated carbon through dynamic simulation. The diffusion coefficient of NO molecules in the pores of activated carbon is calculated to be 1.2×10^{-4} cm^2/s, which indicates that the diffusion rate of NO molecules in the pores of activated carbon is relatively slow. It further explains why a certain residence time is required in the actual desulfurization and denitrification process [34,35].

Activated carbon has two functional groups, oxygen-containing and nitrogen-containing [36]. The oxygen-containing functional groups contain carboxyl, lactone, carbonyl, phenolic hydroxyl, and so on. The nitrogen-containing functional groups contain pyrimidine, amide group, milk amine group, phthalamido group, etc. (Figure 4).

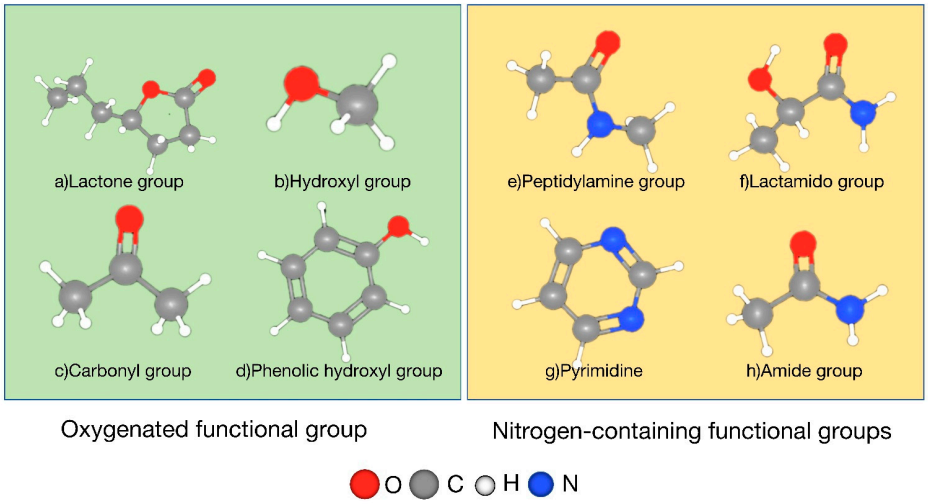


Figure 4. Partial oxygen and nitrogen functional groups on the surface of activated carbon.

Different functional groups on the surface of activated carbon have different effects on desulfurization and denitrification: acidic functional groups such as carboxyl and hydroxyl groups can enhance the physical adsorption and chemical reaction ability of sulfur dioxide [37,38]. The presence of acidic functional groups can increase the wettability of the surface of activated carbon, thereby promoting the dissolution and absorption of sulfur dioxide in the aqueous phase and improving the desulfurization efficiency. However, acidic functional groups usually inhibit the adsorption of nitrogen oxides; basic functional groups such as pyrrole nitrogen and pyridine nitrogen are conducive to the adsorption and conversion of nitrogen oxides [39,40]. Basic functional groups can be used as Lewis base centers to react with acidic sites in nitrogen oxides to promote the adsorption and reduction of nitrogen oxides. However, the contribution of basic functional groups to the adsorption of sulfur dioxide is relatively small. Carbonyl and quinone groups promote the redox reaction of sulfur and nitrogen oxides by redox activity [39], and lactone groups indirectly affect the surface properties and pore structure. In practice, functional groups can be regulated by surface modification to improve the desulfurization and denitrification performance. Activated carbon is mainly composed of carbon elements. Its chemical properties are relatively stable, and it is not easy to react with adsorbates, which makes it able to maintain good adsorption performance in various environments. At the same time, the above oxygen-containing, nitrogen-containing, and other functional groups on

the surface of activated carbon can be chemically adsorbed with some adsorbates to further enhance their adsorption capacity.

2.3. Activated Carbon Flue Gas Desulfurization and Denitrification Technology

In addition to the strong adsorption performance, the catalytic, reduction, and loading capacity of activated carbon enable it to have a good performance in flue gas treatment, and it is an excellent desulfurization and denitrification agent. Since the early 1990s, activated carbon flue gas desulfurization and denitrification technology has become one of the hot spots in domestic academic research. Since 2019, with the deepening of research, activated carbon desulfurization and denitrification technology has been increasingly improved, which has achieved the combined removal of multiple pollutants in flue gas. The removal rate of SO_2 and SO_3 reached 98%, the removal rate of NO_x reached more than 80%, and the removal effect of dust reached less than 10 mg/Nm^3. Because of gas–solid adsorption, there is no liquid water involved in the whole process, so there is no need to treat wastewater. The by-products are mainly H_2SO_4 and S, so they can be recycled [41,42] (Table 1).

Table 1. Activated carbon desulfurization and denitrification technology [43–48].

Technical Steps	Technical Process	Reactive Mode	Reaction Product
Adsorb	Activated carbon adsorbs sulfur dioxide, oxygen, and water by physical adsorption and produces sulfuric acid by chemical reaction. Sulfuric acid is adsorbed on activated carbon and then reacts with water adsorbed on activated carbon to produce sulfuric acid with n crystal water. Ammonia is injected into the flue gas after desulfurization (as a reducing agent, the effect is to reduce nitrogen oxides, namely, nitric oxide and nitrogen dioxide, to nitrogen).	$SO_2 + \frac{1}{2}O_2 + H_2O \overset{\text{Physical adsorption}}{\rightarrow} SO_2^* + \frac{1}{2}O_2^* + H_2O^*$ $\overset{\text{Chemical adsorption}}{\rightarrow} H_2SO_4^* \xrightarrow[\text{Chemical adsorption}]{nH_2O^*} H_2SO_4 \cdot nH_2O^*$ $4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$ $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$	N_2
Desorption	The activated carbon after adsorption is heated to 400 °C in the regeneration tower. At this time, the carbon reacts with sulfuric acid to produce sulfur dioxide.	$C + 2H_2SO_4 \overset{400\,^\circ C}{\rightarrow} 2SO_2 + CO_2 + 2H_2O$	SO_2
Sulphur recovery	1. Preparation of sulfuric acid Method 1: Sulfur dioxide is catalytically oxidized to sulfur trioxide, which reacts with water to form sulfuric acid. Method 2: Sulfur dioxide is introduced into potassium permanganate solution or hydrogen peroxide solution and oxidized by potassium permanganate or hydrogen peroxide. 2. Preparation of ammonium sulfate Ammonium sulfate is prepared by introducing oxygen and ammonia into sulfur dioxide.	Sulfuricacid Method 1: $SO_2 + O_2 \overset{catalyst}{\rightarrow} SO_3 \overset{H_2O}{\rightarrow} H_2SO_4$ Method 2: $5SO_2 + 2KMnO_4 + 2H_2O \rightarrow K_2SO_4 + 2MnSO_4 + 2H_2SO_4$ $SO_2 + H_2O_2 \rightarrow H_2SO_4$ Preparation of ammonium sulfate $2SO_2 + O_2 + 2H_2O + 4NH_3 \rightarrow 2(NH_4)_2SO_4$	H_2SO_4 $(NH_4)_2SO_4$

Due to its developed pore structure and huge specific surface area, activated carbon can physically adsorb SO_2, O_2, H_2O, and NO_x in flue gas. The active sites such as oxygen-containing functional groups on the surface can also catalyze the oxidation reaction of sulfur dioxide to produce sulfuric acid and store it in the pores. When heated to 400 °C in the regeneration tower, the thermal desorption and chemical reaction are coordinated, and the carbon reacts with sulfuric acid to release SO_2, so as to realize the regeneration of activated carbon. However, excessive regeneration will destroy its pore structure. When ammonia is injected for denitrification, activated carbon provides an interface for the reaction. However, due to the poor catalytic selectivity of active sites, frequent side reactions, and the influence of gas–solid mass transfer resistance and the operating conditions, the denitrification efficiency is limited. In the process of sulfur recovery, the catalytic oxidation method converts SO_2 into SO_3 with the help of the catalyst to prepare sulfuric acid, and the oxidation absorption method uses a strong oxidant to achieve this conversion. Ammonium sulfate can be prepared by introducing oxygen and ammonia. In view of the existing problems, it is expected to improve the adsorption and catalytic activity of nitrogen oxides, improve the gas–solid mass transfer efficiency, and promote the further development of this technology by loading transition metal or non-noble metal elements to modify activated carbon and regulate the pore structure of activated carbon [49].

3. Different Modification Methods of Activated Carbon and Its Removal Effect on Sulfur and Nitrate in Flue Gas

In order to seek high denitrification efficiency of activated carbon, scholars have conducted in-depth research on its pore structure, pore size, specific surface area, and surface functional group type. Studies have shown that the non-polarity, hydrophobicity, chemical stability, and thermal stability of activated carbon itself have created good conditions for its activation and modification [50–52]. Through physical and chemical modification methods, the adsorption and catalysis of activated carbon are improved to meet the high-efficiency denitrification requirements of activated carbon for flue gas.

3.1. Common Modification Methods of Activated Carbon

The modification methods of activated carbon can be divided into physical modification and chemical modification [53]. Among them, physical modification includes high-temperature heat treatment modification and microwave modification. Chemical modification includes oxidation modification, acid–base modification, metal modification, and plasma modification, as shown in Table 2:

Table 2. Modification of activated carbon [54–60].

Method	Modification Medium	Characteristics After Modification	Merit	Defect	Temperature	Type
High temperature	Inert gas (N_2/Ar) In oxidizing or oxidizing atmospheres (CO_2/water vapor)	The specific surface area becomes larger, and the internal micropore volume expands.	The chemical properties are stable, and the adsorption capacity is stronger.	Pore contraction.	500–900 °C	Physical modification
Microwave	Physical microwave field	New pores are generated, and the pore structure and surface functional groups are changed.	Fast heating, high efficiency, low energy consumption, easy to control.	The carbon skeleton and pore size shrinkage become smaller.	300–800 °C	Physical modification

Table 2. *Cont.*

Method	Modification Medium	Characteristics After Modification	Merit	Defect	Temperature	Type
Oxidation	Gas phase oxidation (O_3) liquid phase oxidation (HNO_3, H_2O_2, $KMnO_4$)	With the increase in oxygen-containing functional groups, the specific surface area increases.	The adsorption capacity of polar substances is enhanced.	The adsorption capacity of non-polar substances is weakened.	Gas phase oxidation at room temperature 300 °C Liquid phase oxidation at room temperature to 90 °C	Chemical modification
Reduction	Gas phase reduction (H_2, NH_3, N_2) and liquid phase reduction (N_2H_4)	The number of basic functional groups is increased, the specific surface area is increased, the number of pores is increased, and the number of hydroxyl groups is increased.	The adsorption capacity of non-polar substances is increased.	The adsorption capacity of polar substances is weakened.	Gas phase reduction 30–1000 °C Liquid phase reduction at room temperature to 100 °C	Chemical modification
Acid base	Acidic (HCL, H_2SO_4, H_3PO_4) alkaline (NaOH, KOH, NH_3)	The number and type of chemical functional groups is changed.	A special activated carbon for the adsorption of a substance can be obtained.	The specific surface area decreases, and the adsorption capacity decreases.	Acidic at room temperature to 90 °C Alkaline at room temperature to 120 °C	Chemical modification
Supported metal	Metal salts (Fe (NO_3), $CuCl_2$, $AgNO_3$) metal oxides (ZnO, CuO, TiO_2)	The pore structure changes, and the types of chemical functional groups change.	Produce new active sites, improve selectivity, and prolong the service life of activated carbon.	Adsorption of different substances requires loading different metal ions, atoms, or compounds.	Impregnated at room temperature to 80 °C Burning activation 200–950 °C	Chemical modification
Plasma	Oxidizing gases (O_2/air) Reductive gas (H_2/HNO_3) Inert gas (N_2, Ar) Composite gas (O_2/Ar, N_2/H_2)	The number and type of functional groups is changed, and the specific surface area and micropore melting are increased.	High efficiency, fast speed, energy saving.	The operation cost is high, and the technology is difficult.	Heat treatment temperature from room temperature to 200 °C Drying temperature 80–120 °C Calcined at 200–600 °C	Chemical modification

Physical modification is performed by heating the activated carbon by providing an inert gas atmosphere (high-temperature heat treatment) or microwaves. The purpose is to increase the micropore volume and specific surface area of the activated carbon, thereby increasing its adsorption capacity. However, in the case of local sintering, the pore size will shrink to a certain extent, which will affect the adsorption capacity of activated carbon. In chemical modification, oxidant, reducing agent, and non-redox means are used to change the structure and quantity of functional groups and enhance the adsorption capacity of activated carbon. For example, in reduction modification (taking H_2 as an example), R-OH (hydroxyl group on the surface of activated carbon) + $H_2 \rightarrow$R-H + H_2O, the non-polarity

of the activated carbon surface is enhanced, but the adsorption of polar substances is weakened. On the contrary, with oxidation modification (taking ozone as an example), $C + O_3 \rightarrow C\text{-}O\text{-}O + O_2$ forms peroxide functional groups, the surface polarity of activated carbon is enhanced, and the adsorption of non-polar substances is weakened. Acid–base modification will change the pore structure of activated carbon while strengthening the adsorption. As the concentration of the modified solution increases, the degree of collapse and crack deepens, resulting in a decrease in the specific surface area and affecting the adsorption capacity.

For metal loading modification, metal ions or metal compounds are introduced into the surface or pores of activated carbon. Additionally, the metal is combined with the functional groups on the surface of activated carbon by chemical reaction. After metal loading, first of all, the chemical properties of the activated carbon surface can be changed, new active sites can be generated, and the adsorption and catalytic ability of the material can be improved. Secondly, through the interaction between the metal and activated carbon, the synergistic effect is exerted, the selectivity is improved, the target is accurately adsorbed, and the overall performance of the material is enhanced. Thirdly, the stability of activated carbon after metal loading modification is good, which prolongs the service life of activated carbon. The reusability of the metal can also be improved by the reducibility of the activated carbon itself and the characteristics of the loaded metal.

3.2. Modification of Metal-Loaded Activated Carbon

According to the characteristics of flue gas and the needs of desulfurization and denitrification, combined with the advantages and disadvantages of various activated carbon modifications, metal loading modification is an ideal activated carbon modification method in activated carbon desulfurization and denitrification technology. Metal loading modification can not only repair the pore structure of activated carbon but also enhance the chemical properties of activated carbon [53]. In the calcination stage, the pore structure evolution of activated carbon showed a significant temperature–time–concentration synergistic effect. When the treatment temperature is in the range of 400–500 °C, the constant temperature time is 1–1.5 h and the solution concentration is in the range of 10–15%. The pores of activated carbon show the characteristics of multi-level pore development: the specific surface area is significantly increased from the original value, the highest increase can reach about 50%, the average pore volume is increased to 0.5–0.7 cm^3/g, the proportion of micropores is increased to about 80%, while the average pore size shows a shrinking trend, down to 1.7–2.0 nm. This structural optimization is due to the fact that the high temperature promotes the pyrolysis and recombination of the precursor, and the increase in the solution concentration strengthens the chemical etching effect. This further refines the micropore structure and promotes the enhancement of the meso-micropore connectivity [61]. When activated carbon is used as a catalytic carrier, it can produce a catalytic adsorption effect on different gases by loading different metal elements or metal compounds. For SO_2 and NO_x in sintering flue gas, metal or metal compounds can be selectively incorporated into activated carbon for modification to improve the adsorption of activated carbon to two gases. There are three main methods for loading metal-modified activated carbon, as shown in Table 3:

Table 3. Modification method of supported metal activated carbon [61–64].

Loading Method	Loading Process	Technological Superiority	Technical Bug
Immersion method	The activated carbon is soaked in metal salt solution. After a period of time, the activated carbon is dried by high-temperature calcination.	Low cost, easy to operate.	A long time will form metal particles.
Sol-gel method	The metal salt solution reserve solution is made into metal salt sol by mixing, stirring, and other processes; then activated carbon is added, and then it is evaporated, dried, cooled, and sealed.	The reaction temperature is low, it is easy to carry out, and the reactants are uniformly mixed. The prepared activated carbon has a large specific surface area and high metal activity.	Long production cycle, will produce harmful substances.
Solid-phase synthesis method	Activated carbon and technical salts are ground in a mortar or ball mill.	High selectivity, high yield, simple process.	Slow diffusion, slow reaction, load effect is not easy to control.

In the field of activated carbon supported metal modification, the impregnation method, sol-gel method, and solid-phase synthesis method show different technical characteristics. The impregnation method realizes the load through the capillary penetration and thermal decomposition of the metal salt solution. For example, after the CuO-loaded coal-based activated carbon is calcined at 500 °C, the SO_2 adsorption capacity is increased to 350 mg/g [65], but there are problems of uneven metal dispersion and pore blockage [66]. The sol-gel method generates nano-metal oxides in situ by the hydrolysis–condensation reaction. For example, after calcination at 500 °C, the photocatalytic degradation efficiency of phenol reached 90% [67], but the process is complicated and the cost is high. The solid-phase synthesis method forms an alloy system by mechanical mixing and high-temperature calcination. For example, after calcination at 800 °C, the methane conversion rate of Ni-MoO_2 supported petroleum coke-based activated carbon reaches 95%, and the carbon deposition resistance is excellent, but the energy consumption is significantly higher than other methods [68,69]. The three methods are suitable for gas adsorption, photocatalysis, and high-temperature catalysis, respectively. The choice depends on the type of supported metal, dispersion requirements, and process economy.

The impregnation method achieves loading by soaking activated carbon in metal salt solution and calcining at high temperature. The process has simple steps, requiring no complex sol preparation or mechanical grinding, and the raw material and operation cost are lower. The process only involves soaking and calcination; thus, the technical threshold is low, the equipment requirements are not high, and it is easy to implement. From the perspective of application scenarios, the impregnation method is suitable for the field of gas adsorption (such as CuO loading coal-based activated carbon to increase the SO_2 adsorption capacity). Although there is the problem of uneven metal dispersion, its basic loading mechanism still has practical value in specific fields (such as adsorption scenarios with relatively non-extreme dispersion requirements). With the characteristics of a low cost and easy operation, it has become the preferred solution for basic modification requirements. Using the characteristics of the strong adsorption of activated carbon, metal ions, metal elements, or metal compounds are first adsorbed to the surface of activated carbon. Next, the metal ions are reduced to low-valent ions or elements by the reduction of carbon atoms under certain conditions. During the reaction of metal elements with activated carbon, the pore structure of activated carbon changes, and the surface chemical functional

groups are abundant. Some metal elements also have redox ability. For example, the multivalent characteristics of transition metal oxides (such as MnO_2) ($Mn^+/Mn^{3+}/Mn^{2+}$) can undergo reversible redox reactions during the adsorption process, which can provide more adsorption sites for activated carbon and increase the adsorption capacity of activated carbon. Therefore, the activated carbon can be changed from a single physical adsorption to a physical and chemical double adsorption [70]. The loading process is shown in Figure 5.

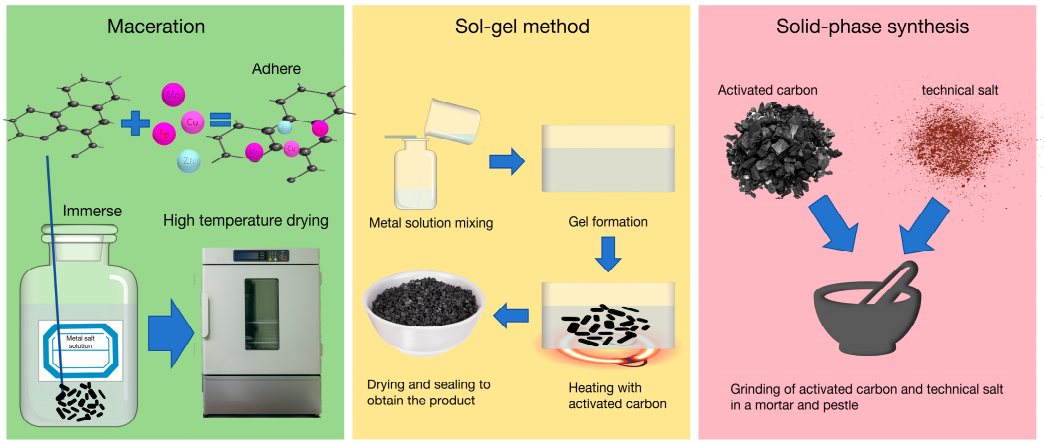


Figure 5. Modification method of metal-loaded activated carbon.

Smathi et al. [71] prepared carbon-based adsorbents by impregnating four metal oxides of Ni, V, Fe, and Ce with palm shell activated carbon. The removal of SO_2 and NO_x in simulated flue gas was studied in a fixed bed reactor. The results showed that the activated carbon impregnated with CeO_2 had the strongest adsorption capacity for SO_2 and NO_x. Quan [72] prepared Mn/AC, Fe/AC, and Cu/AC carbon-based metal catalysts by the equal volume impregnation method and studied the removal of SO_2 and NO_x in simulated flue gas in a fixed bed reactor. The results showed that the Mn/AC catalyst had a good denitrification function at a certain temperature (150–200 °C), but there was also a rapid decrease in catalytic activity. In view of the poor stability of metal elements, a series of Fe-Mn/AC catalysts were prepared by the equal volume impregnation method. The results showed that Fe and Mn had a strong synergistic effect, and a new active component, $Fe_3Mn_3O_8$, was formed, which significantly improved the denitration performance and catalytic stability of the catalyst. Li Yuantao [73] et al. prepared single-component Cu and two-component Cu-Ni metal oxide supported activated carbon by the impregnation method. The results showed that 6% CuO/AC had the best desulfurization and denitrification performance at a certain temperature (120 °C). Under this condition, loading 5% NiO could further improve the desulfurization and denitrification performance, and 5% NiO-2% CuO/AC had the best effect. Sun [74] used Fe_2O_3 load to modify activated carbon to prepare an Fe_2O_3/AC adsorbent. The preparation conditions of the Fe_2O_3-modified activated carbon adsorbent and the effect of the adsorption process conditions on the removal of hydrogen sulfide by activated carbon were investigated in a fixed bed reactor. The results showed that the desulfurization rate of the Fe_2O_3/AC adsorbent was as high as 99.4% when the mass of Fe_2O_3 was 1:1, the activated carbon was dried at 80 °C for 36 h, and the adsorption condition was 60 °C. The supported metal oxides provided the reaction driving force through the redox cycle and enhanced the chemical adsorption specificity through the surface acidic sites, thereby improving the adsorption capacity and stability of activated carbon.

In experiments on loading metal-modified activated carbon, it was found that the cost of loading noble metal-modified activated carbon was high, and the stability of loading metal-modified activated carbon was poor. Meanwhile, the adsorption effect of loading

non-precious metal oxide-modified activated carbon was good, the production cost was low, the preparation process was simple, and it was easy to store, which was the best metal type for loading metal-modified activated carbon.

3.3. Loading Non-Noble Metal Oxide Activated Carbon Desulfurization and Denitrification

Among the many non-precious metal oxides, activated carbon modified with Fe_2O_3, CuO, ZnO, and Mn_2O_3 has the best desulfurization and denitrification effect. Taking Fe_2O_3-modified activated carbon as an example, the characterization of modified activated carbon was explored, and the optimum preparation conditions for the desulfurization and denitrification of activated carbon modified by non-precious metal oxides were summarized.

Xue Limei et al. [75] used coconut shell activated carbon as the raw material, with 3% Fe_2O_3 loading, heated at 500 °C for 180 min to modify activated carbon. The pore size of the modified activated carbon was significantly reduced, and the Fe_2O_3 crystal was relatively evenly distributed on the surface of the activated carbon. This was embedded in the inner wall of the activated carbon macropores, so that the original macropores became numerous small micropores, thereby increasing the specific surface area of the modified activated carbon. Yin Shoulai [76] et al. obtained Fe_2O_3/AC catalyst by the impregnation method. To obtain this, they added activated carbon ground powder to deionized water and $Fe(NO_3)_3 \cdot 9H_2O$ solution, stirred it magnetically for 120 min, followed by drying and roasting. The modified Fe_2O_3/AC catalyst had strong stability, and the main pore size was less than 4 nm. The active component, iron oxide, mainly existed in the form of γ-Fe_2O_3 crystals. The increase in the Fe^{3+} and surface adsorbed oxygen O_β contents improved the low temperature selectivity and reactivity of Fe_2O_3/AC. Hao Ke [61] prepared Fe_2O_3/AC by the impregnation method. The activated carbon was soaked in Fe_2O_3 nitrate solution with different concentrations (5%, 10%, 15%, 20%) for 12 h, then placed in a constant temperature water bath at 60 °C for 6 h, and then ammonia was added to neutralize the pH value of the activated carbon. Four parts of quantitative activated carbon were taken and heated under N_2 protection at a certain temperature (300 °C, 400 °C, 500 °C, 600 °C) and a certain time (1 h, 1.5 h, 2 h, 2.5 h). The characterization of the modified activated carbon was detected by XRD, SEM and BET, and the optimal characterization preparation conditions for loading Fe_2O_3/AC were obtained, as shown in Figure 6:

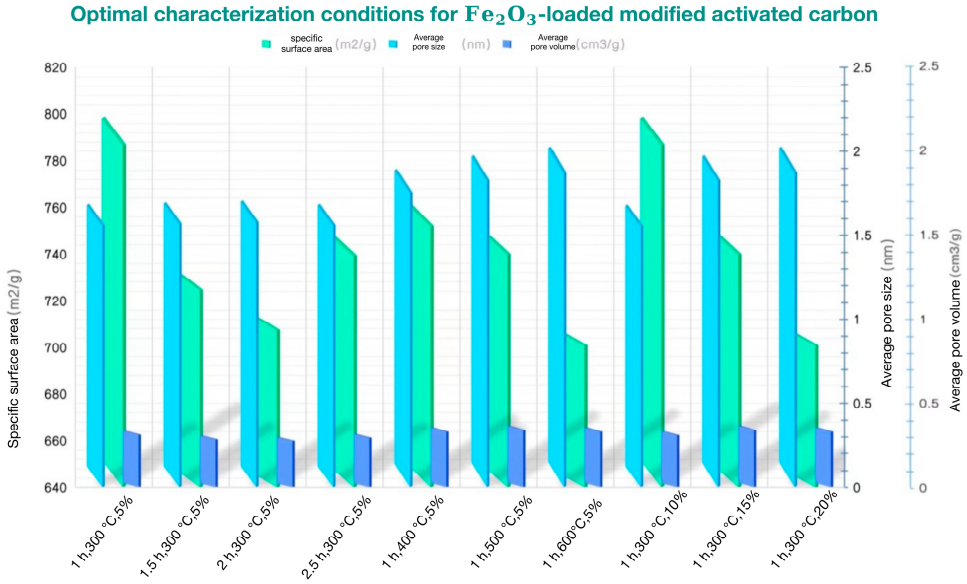


Figure 6. The best characterization conditions of Fe_2O_3-modified activated carbon.

From Figure 6, it can be seen that the characterization change of the loaded Fe_2O_3/AC prepared by the impregnation solution concentration of 10%, the heating temperature of 400 °C, and the heating time of 1 h is the most conducive to flue gas desulfurization and denitrification. The enhancement of the desulfurization and denitrification ability of activated carbon loaded with non-noble metal oxides is mainly due to the change in pore structure of activated carbon after modification from the perspective of physical adsorption. The pore structure and intermolecular force of activated carbon are enhanced, and the total amount of gas molecules captured by the activated carbon pores due to van der Waals force is increased. From the perspective of electrostatic forces, if the surface of the activated carbon involved in the load is positively charged, it will attract ions with negative charge. On the contrary, if the surface is negatively charged, it will attract positively charged ions.

In terms of chemical adsorption, the introduction of hydroxyl groups on the surface of Fe_2O_3 by chemical modification can significantly improve the removal performance of activated carbon for sulfur dioxide. The mechanism of action is reflected in two aspects: firstly, as an active site, hydroxyl groups can react with sulfur dioxide molecules by the acid–base neutralization reaction or coordination reaction and strengthen the fixation of sulfur dioxide on the surface of the material by chemical adsorption (1); secondly, the activated carbon loaded with Fe_2O_3 reacts in the presence of oxygen and water (2) and can react by catalytic oxidation (3). Sulfur dioxide is converted into sulfur trioxide, and sulfur trioxide is desorbed by Reaction (4). Sulfur trioxide reacts with water to form sulfuric acid to achieve sulfur fixation and conversion, that is, Reaction (5). This synergistic effect not only enhances the adsorption capacity through surface hydroxyl groups but also enhances the conversion efficiency of sulfur through the catalytic oxidation process, thereby significantly improving the comprehensive performance of activated carbon-based materials in flue gas desulfurization. The reaction process is as follows (* represents the adsorption state in the equation):

$$\text{Adsorption of sulfur dioxide}: \ SO_2(g) \rightleftharpoons SO_2^* \quad (1)$$

$$\text{Oxygen adsorption}: \ O_2(g) \rightleftharpoons O_2^* \quad (2)$$

$$\text{Formation of sulfur trioxide}: \ SO_2^* + O_2^* \rightleftharpoons SO_3^* \quad (3)$$

$$\text{Sulfur trioxide desorption}: \ SO_3^* \rightleftharpoons SO_3(g) \quad (4)$$

$$\text{The formation of sulfuric acid}: \ SO_3 + H_2O \rightleftharpoons H_2SO_4 \quad (5)$$

$$\text{The total reaction is the following}: \ 2SO_2 + 2H_2O + O_2 \overset{Fe_2O_3/AC}{\rightarrow} 2H_2SO_4 \quad (6)$$

The absorption of NO_x by Fe_2O_3/AC is absorbed by the redox reaction (taking NO as an example). Fe_2O_3 has a certain oxidizability. In the presence of oxygen, nitric oxide can be oxidized to nitrogen dioxide (10). The generated nitrogen dioxide can react with water (the activated carbon adsorption system may contain a small amount of water) to generate nitric acid. The adsorption of acidic gases in nitrogen oxides (NO_2 as an example) occurs. When nitrogen oxides exist in this acidic gas, the basic sites on the activated carbon or the hydroxyl groups on the surface of Fe_2O_3 react (11) (the hydroxyl groups on the surface of Fe_2O_3 are involved in the reaction) to increase the adsorption capacity of activated carbon for nitrogen oxides.

The above reaction process is as follows:

$$Fe_2O_3 - OH + SO_2 \rightarrow Fe_2O_3 - OSO_2H \quad (7)$$

$$Fe_2O_3 - AC + SO_3^{2-} \rightleftharpoons Fe_2O_3 - AC - SO_3^{2-} \quad (8)$$

$$Fe_2O_3 - AC + HSO_3^{+} \rightleftharpoons Fe_2O_3 - AC - HSO_3^{+} \quad (9)$$

$$2NO + O_2 \xrightarrow{Fe_2O_3/AC} 2NO_2 \quad (10)$$

$$3NO_2 + H_2O \rightarrow 2HNO_3 + NO \quad (11)$$

$$2 - OH + 2NO_2 \rightleftharpoons -O - NO_2 + H_2O + NO_3^- \quad (12)$$

Although the adsorption of metal-loaded activated carbon has been improved, there are still some problems. For example, the catalytic efficiency of non-noble metal active sites is limited. In some reactions that require high activity, the ideal reaction rate may not be achieved. After microwave treatment of activated carbon, this problem can be well improved. Microwave irradiation loading non-noble metal oxide activated carbon can improve the dispersion of metals on activated carbon, so that the metals are more evenly distributed on the surface of activated carbon, so as to improve the exposure of metal active sites and accelerate the reaction rate. Microwave heating is an internal heating method, which can heat the activated carbon and the loaded metal at the same time. Therefore, the redox reaction on the surface can be carried out efficiently, so that the flue gas desulfurization and denitrification is more efficient.

4. Loaded Non-Noble Metal Oxide Activated Carbon Microwave Flue Gas Desulfurization and Denitrification

4.1. Activated Carbon Microwave Desulfurization and Denitrification

Microwaves are high-frequency electromagnetic waves with a wavelength of 1–1000 mm and a wave frequency range of 300–3000 GHz, which is between general radio waves and light waves [77]. It mainly has three characteristics: penetration, reflection, and absorption [78]. Microwave heating is a process involving a microwave directly coupled with the polar molecules in the reaction substance to achieve the effect of targeted heating [79]. In addition, the containers used for microwave heating are mostly transparent materials such as polypropylene and glass. Based on the loss mechanism of electromagnetic waves interacting with substances, and combining the advantages of microwave heating with the characteristics of the container materials, this approach realizes synchronous heating of the entire material being heated [80] (Figure 7). Compared with traditional heating methods, microwave heating has the advantages of high energy utilization, high heating efficiency, strong heating selectivity, and safe and controllable heating process [81].

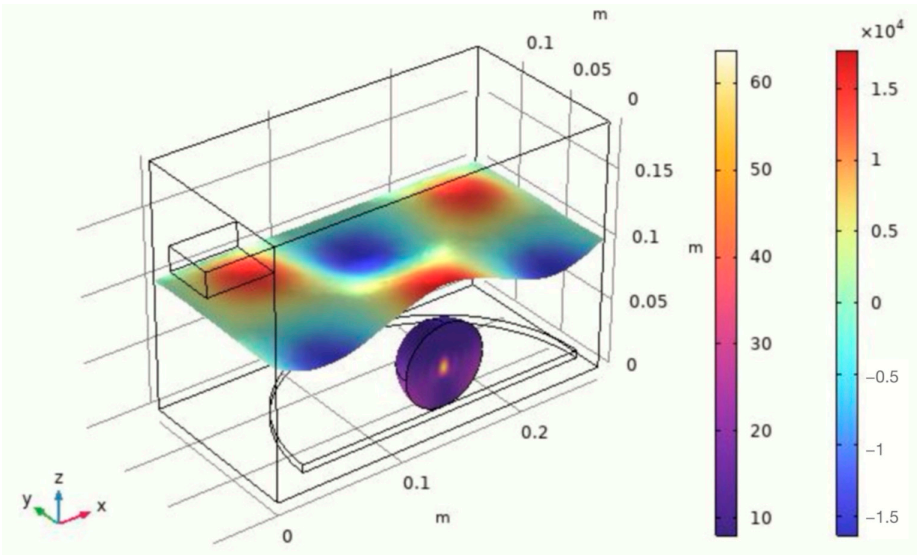


Figure 7. Heat distribution map of microwave heating.

Activated carbon microwave flue gas desulfurization and denitrification technology involves using activated carbon to adsorb harmful substances in flue gas. When the flue gas passes through the activated carbon bed, harmful gases (SO_2 and NO_x) are adsorbed by activated carbon in its own internal pores. Under the action of microwave, SO_2 is reduced to sulfur, and NO_x is reduced to nitrogen, so as to achieve the purpose of the simultaneous removal of sulfur and nitrate from the flue gas [82,83]. The thermal effect and non-thermal effect under microwave irradiation play an important role in flue gas desulfurization and denitrification [84–87]. The phenomenon that matter absorbs microwave energy to produce heat during microwave irradiation is called the thermal effect of microwave [88]. The reason why microwave irradiation of activated carbon can produce the thermal effect and high efficiency desulfurization and denitrification is that microwave heating belongs to intramolecular heating. Moreover, the activated carbon material has delocalized π electrons due to the sp2 hybrid carbon network. On the one hand, it can interact with the microwaves, prompting activated carbon to effectively absorb microwave energy and provide an energy source for desulfurization and denitrification reactions; on the other hand, under the influence of high-speed rotating electromagnetic waves, the delocalized π electrons change the internal electromagnetic field of the activated carbon. Therefore, the internal molecules exhibit dipole polarization motion characteristics, triggering the rotation, collision, and friction of the reaction molecules. The internal molecules also convert microwave energy into traditional heat energy, realizing the overall temperature rise of activated carbon. This can also create a suitable reaction environment and promote the reduction of sulfur dioxide to elemental sulfur and nitrogen oxides to nitrogen and achieve the goal of efficient desulfurization and denitrification [89].

The non-thermal effect of microwave refers to the effect of the microwaves acting on the reactants other than the thermal effect [90]. The heating rate of microwave irradiation is related to the polarity of the material. The complete tiled structure of activated carbon is a non-polar state. The uneven distribution or fracture of charge will cause local resonance coupling energy transfer with microwaves, and many regions with different temperatures will appear to form local active sites. The temperature of these active sites is significantly higher than that of the other regions, so they are called 'hot spots'. In the process of microwave irradiation of activated carbon, the heat or temperature distribution of activated carbon will be uneven, resulting in a local temperature that is too high, the formation of an obvious temperature gradient, and the promotion of the desulfurization and denitrification reaction, the so-called hot spot effect [91]. During the desulfurization and denitrification of activated carbon by microwave irradiation, SO_2 and NO_x can be reduced without a higher temperature, and a higher temperature gradient is formed on the activated carbon. From the center of the activated carbon to the surface, the temperature gradually decreases, so that the product gas of the flue gas reduction rapidly diffuses out [92], as shown in Figure 8.

In the microwave desulfurization and denitrification reaction of activated carbon, activated carbon is not only the adsorbent of SO_2 and NO_x but also the reducing agent. The main redox reactions are as follows [93]:

$$xC + 2NO_x \rightarrow N_2 + xCO_2 \quad (13)$$

$$xC + NO_x \rightarrow 0.5N_2 + xCO \quad (14)$$

$$xC + SO_2 \rightarrow S + CO_2 \quad (15)$$

$$2C + SO_2 \rightarrow S + 2CO \quad (16)$$

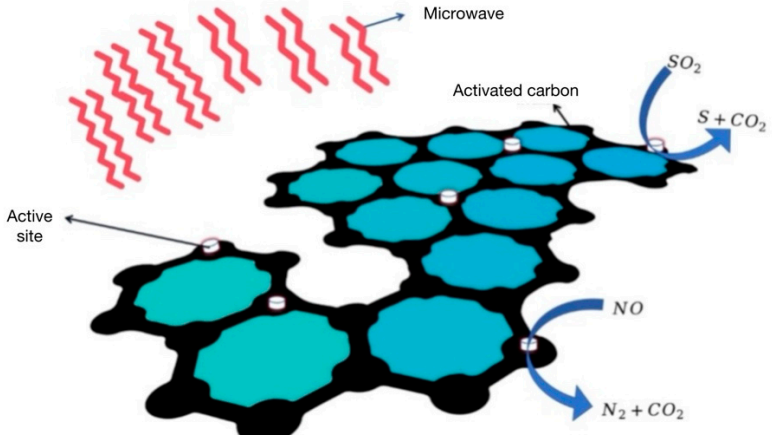


Figure 8. Mechanism of desulfurization and denitrification of activated carbon by microwave irradiation.

In the whole process of desulfurization and denitrification, Reactions (13) and (15) are exothermic reactions, which can be carried out at a lower temperature. Furthermore, Reactions (14) and (16) are endothermic reactions, which can be carried out at a higher temperature under the conventional heating mode. The microwave irradiation activated carbon thermal reduction of sulfur nitrogen oxide reaction does not need to heat the activated carbon to the conventional reaction temperature. Additionally, it can lead to SO_2 and NO_x reduction, to achieve a higher efficiency of sulfur and nitrate removal.

In the process of microwave desulfurization and denitrification of activated carbon, the pore volume and pore size of activated carbon increase under the combined action of the thermal effect and the non-thermal effect, and the rapid increase in temperature caused by the thermal effect reduces the specific surface area of the activated carbon skeleton [94]. Under the same conditions, the microwave power affects the removal efficiency of sulfur and nitrate in the flue gas. The oxygen content on the surface of activated carbon decreases with the increase in microwave power. This is due to the fact that heating the activated carbon under microwave irradiation in the flue gas atmosphere will make its surface part of the oxygen-containing functional groups in the form of CO or CO_2 removal [95]. The greater the microwave power, the more oxygen-containing functional groups are removed. With the continuous increase in microwave power, the alkaline characteristics of the activated carbon surface are continuously enhanced. After microwave irradiation, the acidic groups of the activated carbon are decomposed, and its chemical characteristics tend to be alkaline, which is more conducive to the efficient removal of pollutants such as SO_2 and NO_x [96].

4.2. Loaded Non-Noble Metal Oxide Activated Carbon Microwave Desulfurization and Denitrification

The synergistic technology of microwave and activated carbon loaded with non-precious metal oxides for flue gas desulfurization and denitrification can make full use of the propagation and heating characteristics of microwaves in flue gas. It can also combine the advantages of adsorption, catalysis, and regeneration of modified activated carbon in the process of flue gas desulfurization and denitrification. This provides a new path for flue gas desulfurization and denitrification.

Microwave desulfurization and denitrification of activated carbon loaded with non-noble metal oxides has been widely studied in academia. Jinxin [97] used 420 W microwave to irradiate activated carbon loaded with ZnO, Mn_2O_3, and CuO to carry out desulfurization and denitrification comparative experiments on flue gas with a flow rate of 0.15 m^3/h. The results showed that under the same conditions, the denitrification efficiency of unsupported non-noble metal oxide activated carbon could reach 80.5% under microwave irradiation. After loading the three non-noble metal oxides, the denitrification efficiency

reached 87.4%, 89.1%, and 92.5%, respectively. The desulfurization efficiency did not change much, or even decreased, because the non-noble metal oxides hindered the reduction of SO_2 by activated carbon. Firstly, non-precious metal oxides will occupy the active sites on the surface of activated carbon for the adsorption and reduction of sulfur dioxide, reducing its contact area. Secondly, the loading of non-noble metal oxides changes the surface chemical properties and electronic structure of activated carbon, affecting the adsorption and reduction of sulfur dioxide. Thirdly, the side reactions catalyzed by non-precious metal oxides consume the substances required for the reduction of sulfur dioxide or generate intermediate products that hinder the reduction reaction, thus inhibiting the reaction. Li [98] used microwave irradiation to load Mn_2O_3 activated carbon for flue gas denitrification experiments and explored the effects of the temperature, non-metallic oxide loading, microwave power, space velocity, and oxygen content on flue gas denitrification. The results showed that the optimum loading of Mn_2O_3 is 3–5%. Under the same conditions, the higher the microwave power is, the higher the denitrification efficiency, the higher the oxygen content, and the higher the denitrification rate, but the higher the space velocity is, the lower the denitrification rate. When the temperature reaches 400 °C, the denitrification rate is close to 100%. Liu [99] obtained Fe_2O_3-loaded coal-based carbon by the precipitation method and carried out flue gas denitrification experiments under microwave irradiation. The results showed that the denitrification rate could reach 95% when the microwave power was 250 W. Hao Ke [62] modified activated carbon by loading four non-precious metal oxides of Fe_2O_3, CuO, Mn_2O_3, and ZnO by the impregnation method and explored the effect of different conditions on the efficiency of flue gas desulfurization and denitrification under microwave irradiation. The results showed that under the same conditions, the desulfurization and denitrification effect of activated carbon loaded with the four non-metallic oxides was better than that of ordinary activated carbon. When the temperature is 420 °C, the desulfurization effect of four non-metallic oxides is close to 100%, while the denitrification effect is different. According to the amount of denitrification, the order is Fe_2O_3/AC > CuO/AC > Mn_2O_3/AC > ZnO/AC. The experimental process of the above conclusions is shown in Figure 9:

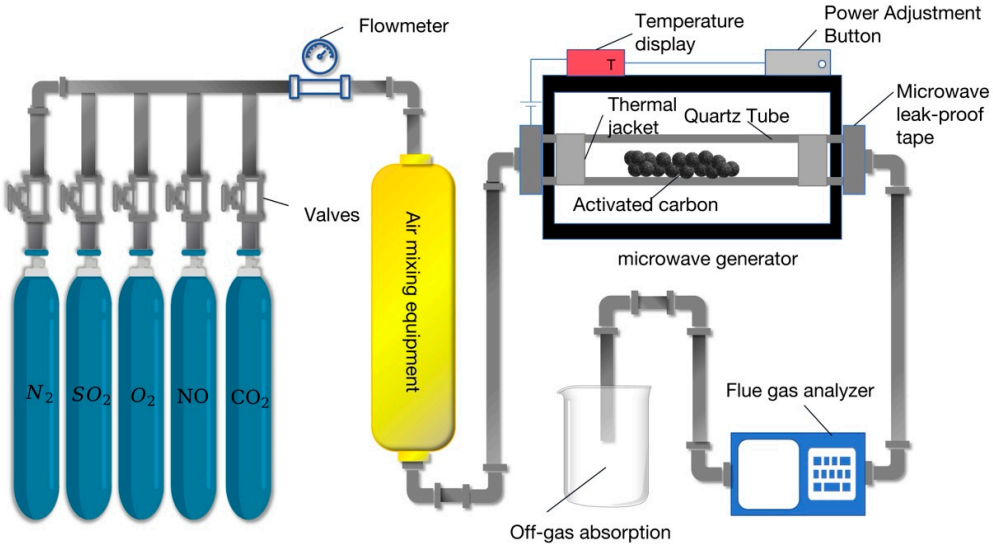


Figure 9. Microwave desulfurization and denitrification experimental device loaded with non-noble metal oxide activated carbon.

Compared with the traditional activated carbon microwave flue gas desulfurization and denitrification, the non-noble metal oxide loaded activated carbon microwave flue gas desulfurization and denitrification mainly reflects three advantages. The advantages are im-

proving the efficiency of flue gas sulfur and nitrate removal, reducing energy consumption and operating costs, and reducing secondary pollution.

(1) The removal efficiency of sulfur and nitrate in the flue gas is improved. First of all, the traditional activated carbon microwave flue gas desulfurization and denitrification technology mainly depends on the adsorption of activated carbon. After the activated carbon is loaded with non-noble metal oxides, the original activated carbon becomes a catalyst or catalyst carrier under the action of microwaves. While exerting the adsorption effect, it can also effectively promote the reaction of desulfurization and denitrification. Secondly, after the non-metallic oxide is loaded on the surface of the activated carbon, it will provide more active sites for the activated carbon under the action of microwaves. The abundant active sites provide more adsorption space for SO_2 and NO_x, which effectively alleviates the competitive adsorption of SO_2 and NO_x. Thirdly, the loading of non-noble metal oxides enhances the microwave absorption performance of activated carbon, which is beneficial to the rapid heating of activated carbon, forming a high temperature gradient and increasing the reaction rate.

(2) Reduced energy consumption and operating costs. Firstly, activated carbon loaded with non-precious metal oxides is not easily saturated by sulfur oxides and nitrogen oxides in the process of flue gas desulfurization and denitrification, which prolongs the service life of activated carbon. Secondly, there is no need for tedious and accurate technical control in the whole technical link, which reduces the cost of human resources and other material costs. Thirdly, due to the lack of some cumbersome technology to control the environment, the cost of equipment in construction is relatively reduced.

(3) It reduces the by-products such as CO, sulfate, and nitrate and reduces the secondary pollution to the environment. Firstly, microwave radiation loading of non-noble metal oxides will cause electrons inside the activated carbon to transition, resulting in a thermal effect. This thermal effect can promote non-noble metal oxides becoming better dispersed on the surface of activated carbon and prevent their agglomeration. Secondly, the microwave field can also induce the formation of a local electromagnetic field between the metal and the activated carbon. This affects the conductivity of the activated carbon, and the electron transfer becomes easier between the activated carbon and the non-noble metal. The change changes the electron cloud density around the non-noble metal, which affects the adsorption and activation ability of the reactant molecules. Thirdly, microwave loading of non-noble metal activated carbon will also cause changes in the functional groups on the surface of activated carbon. These changed functional groups interact with non-precious metals to form a special catalytic environment conducive to complete oxidation, making the reaction more inclined to generate carbon dioxide and reducing the generation of carbon monoxide.

4.3. Dilemma Analysis of Microwave Desulfurization and Denitrification of Loaded Non-Noble Metal Oxide Activated Carbon

The microwave desulfurization and denitrification technology of loaded non-noble metal oxide activated carbon has achieved certain results in the experimental research stage. Its desulfurization and denitrification efficiency is better than that of ordinary activated carbon microwave desulfurization and denitrification technology. However, the relevant parameters of the experimental study are set under artificial conditions. There are some differences between the experimental flue gas composition and the real industrial flue gas composition. Therefore, the actual desulfurization and denitrification effect of microwave desulfurization and denitrification technology loaded with non-noble metal oxide activated carbon needs to be further studied. In view of the excellent performance of the microwave

desulfurization and denitrification technology of loaded non-noble metal oxide activated carbon in the experimental process, we strive to make the technology more mature and stable and apply it to the actual production field as soon as possible. In the future, we should continue to carry out in-depth research from the following aspects:

(1) Strive to make the flue gas composition and flue gas environment, through a significant amount of research, more similar to actual industrial emissions. In the current research process, scholars do not fully consider the flue gas environment. In most cases, only the flue gas components that have a direct impact on the experimental results are retained. Although there are studies on other factors such as heavy metal harmful substances, oxygen content, humidity, temperature, acidity, and alkalinity in flue gas, they remain at the basic level of separate research on single index parameters. In the existing literature, there is a lack of research on the microwave desulfurization and denitrification efficiency of non-noble metal oxide activated carbon in real flue gas environments. The amount of flue gas is far from the actual industrial production unit time or standard capacity of flue gas emission standards. Therefore, this technology not only has huge research space but also great research potential.

(2) Strive to explore the microwave irradiation time and the actual ratio and dosage of non-noble metal oxide loaded activated carbon more specifically in the study. In the existing research, in order to reduce the carbon loss of activated carbon, the use of microwave irradiation to load non-noble metal oxides in the research process is relatively short. In the actual production process, as long as the production line does not stop, flue gas emissions will not stop. How to rationally use microwave irradiation in the production practice to maximize the adsorption and catalytic effects of activated carbon loaded with non-noble metal oxides in order to achieve the ideal desulfurization and denitrification efficiency is another subject. The subject must be overcome in the application field of this technology. According to the different application fields and flue gas compositions, exploring the ratio of non-precious metal oxides and activated carbon and finally scientifically controlling the amount of activated carbon are effective ways to control costs.

(3) Strive to design and manufacture the equipment from the perspective of specific practical applications in the research and calculate and control the operating costs. In the current research process, scholars use microwave tube furnaces as microwave generating devices and corundum furnace tubes as activated carbon loading devices. In the production practice, how to design and install the microwave-generating device and how to arrange the activated carbon to achieve the ideal desulfurization and denitrification effect of flue gas are key to the application of this technology. Some scholars have estimated the construction and operation costs of this technology. However, with the change of the times and the upgrading of production capacity, the economics of microwave desulfurization and denitrification technology of non-precious metal oxide activated carbon under the existing production environment have yet to be further verified by scholars.

Conclusions and Prospects

(1) The advantages and disadvantages of the existing activated carbon flue gas desulfurization and denitrification process coexist. The advantage is that it can remove a variety of harmful substances in flue gas at the same time, and the activated carbon itself is cheap; the disadvantage is that the process is old and that the process is too long, resulting in high loss of activated carbon. Improper operation may also produce by-products such as CO and CO_2, resulting in secondary pollution. Therefore,

the process does not occupy a dominant position in flue gas desulfurization and denitrification in the field of iron and steel production.

(2) The modification of activated carbon can not only improve the removal efficiency of flue gas sulfur and nitrate by activated carbon but also improve the regeneration ability of activated carbon. The special physical and chemical properties of activated carbon provide it with good adsorption, catalysis, and reduction properties, and it also has good wave absorption properties. Under the action of microwave, activated carbon can improve its activity and accelerate the reaction rate with sulfur and nitrate in flue gas. The modified activated carbon loaded with non-noble metal oxides (mainly loaded with Fe_2O_3, CuO, ZnO, Mn_2O_3) can also reduce the production of CO at the reaction terminal under the synergistic effect of microwave and improve the microwave absorption performance of activated carbon. It can also increase the active sites on activated carbon and improve the removal efficiency of sulfur and nitrate as a whole, so as to achieve the requirements of low cost, high efficiency, strong stability, and no pollution.

(3) Activated carbon flue gas desulfurization and denitrification technology has great development potential and broad research space. Future research should focus on the optimization of the activated carbon modified load and the development of composite carbon-based materials. The regeneration of activated carbon, the batch loading process, and the multiple influencing factors of activated carbon desulfurization and denitrification under the synergistic effect of microwave irradiation should also be paid attention to. In addition, the advantages and disadvantages of the existing process technology should be summarized in close connection with the actual needs of production. In view of the good removal effect of load non-metallic oxides and microwave irradiation, the equipment should be continuously optimized and upgraded, so as to make greater contributions to flue gas desulfurization and denitrification in the iron and steel industry.

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