

Study on the desulfurization performance of calcium-based desulfurizer and NaHCO₃ desulfurizer

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Research Article

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Abstract

The commonly used Ca-desulfurizers have low desulfurization efficiency, NaHCO₃-desulfurizers can meet the requirements of desulfurization efficiency, but the high price and the difficulty in handling desulfurization products, make dry flue desulfurization technology quite difficult to realize the large-scale application. Preliminary research found a new Ca-desulfurizer, to understand its performance, comparing investigation into desulfurization performance of different Ca-desulfurizer and NaHCO₃-desulfurizer. The results showed that with the high-performance Ca-desulfurizer, conventional NaHCO₃-desulfurizer, and ultrafine NaHCO₃-desulfurizer, the operating time with 100% desulfurization efficiency is 420, 360, and 100 min, when the flue temperature of 100~300 °C, the “break-through” temperature is 260, 200, and 200 °C, expand the use range of desulfurizer flue gas temperature. Regarding the desulfurizer per unit mass, the production costs of ultrafine NaHCO₃-desulfurizer are 5.36 times higher than Ca-desulfurizer. Compared with NaHCO₃-desulfurizer, high-performance Ca-desulfurizer is characterized by several advantages, including high desulfurization efficiency, wider applicable temperatures, and low preparation cost, allowing for significant development potential in flue gas desulfurization.

Highlights

1. Steam jet mill digestion can prepare a high-performance desulfurizer.
2. SJM desulfurizer performance is better than traditional Ca-desulfurizer.
3. The high-performance desulfurizer has a wider desulfurization temperature.
4. SJM desulfurizer is better than NaHCO₃ in cost and efficiency.

Introduction

As a large country that uses coal as its main energy source and high-sulfur coal account for more than half of its coal resources (Chen et al., 2021), the development of advanced desulfurization technology is of great significance to the progression of the national economy (Wang et al., 2020; Zhao et al., 2021). Flue gas desulfurization technology (FGD) is commonly applied for controlling SO₂ emissions worldwide. The dry flue gas desulfurization technology has attracted much attention at home and abroad for several strengths including reliable operation, low project investments, small areas, basically no corrosion problems in the system, and no wastewater discharge. Among them, the cost of desulfurizer accounts for a large part of the total operating cost of flue gas desulfurization equipment. The development of low-cost, high-efficiency and widely sourced desulfurizers has become one of the hot topics in the field of flue gas desulfurization research (Sahoo P and Sahoo, 2014).

Currently, for dry desulfurization projects, with NaHCO₃ as the desulfurization agent, in-furnace injection and pipeline injection are applied and the flue gas temperature can provide good conditions for

desulfurization (Subramanyan and Diwekar, 2005; Wang et al., 2020). According to a previous study, Michael et al (Michael et al., 2007) have discovered that at 400 K (204.5 °C), the SO₂ concentration ranges between 350 and 500 ppm, and the desulfurization efficiency of NaHCO₃ dry powder reaches 40% to 80% when the the-sodium-to-sulfur ratio is between 0.5 and 3.0. Based on research by Wu et al (Wu et al., 2004) for NaHCO₃ powder, when the calcium-sulfur ratio is 0.5-2.5 and the particle size is less than 30 μm, the reaction temperature for the best desulfurization effect is between 127 °C and 150 °C. NaHCO₃ has been employed by the Energy Environmental Engineering and Consulting Firm (Nie et al., 2019) for higher removal efficiency of acid gases such as SO₂, HCl, and HF in the flue gas. NaHCO₃ as compared to slaked lime (Wu et al., 2020; Wu et al., 2019) has higher desulfurization efficiency and utilization rate but requires more raw material cost, and sodium-based desulfurization product, more soluble in water, is more difficult to be treated relative to calcium-based desulfurization product, thus contributing to severe water pollution in the ash yard (Yu et al., 2019). Besides, (Guo et al., 2015) low-temperature SCR denitration catalysts could be activated under 200 °C or even higher temperature, while it has been suggested in numerous experiments the suitable temperature for NaHCO₃ powder is lower than 200 °C (Liu et al., 2021; Kobayashi et al., 2019). In other words, the arrangement of desulfurization operation is arranged before the denitration catalyst would result in significantly low flue gas temperature and marked humidity, and accordingly, it is of great necessity to reheat the flue gas to meet the temperature requirements for activating the low-temperature SCR denitration catalyst (Yang et al., 2020). Contrarily, the arrangement of desulfurization operation after denitration catalyst would make it easier to provide suitable temperature conditions to activate low-temperature SCR denitrification catalyst, but SO₂ in the flue gas will cause physical poisoning of the low-temperature SCR denitrification catalyst (covering with liquid ammonium bisulfate) (Zhou et al., 2009). Therefore, it is of significant necessity to develop a novel technology with relatively high desulfurization efficiency under dry conditions for industrial flue gas requiring low temperature for denitration (Zhou et al., 2011; Song et al., 2021).

Currently, calcium-based desulfurizer is most widely used due to its low price and wide distribution of resources. The desulfurization efficiency and calcium utilization rate achieved by traditionally digested calcium-based desulfurizers are generally low, which prompts investigation into more methods to enhance the desulfurization efficiency and utilization rate of calcium. It has been indicated in a preliminary analysis that a steam jet mill could be applied to prepare high-performance calcium-based desulfurizers after pulverization and digestion (Lū et al., 2020; Lū et al., 2020). The current research focused on comparing the desulfurization performance among high-performance calcium-based desulfurizers, traditional desulfurizers, and sodium-based desulfurizers to develop a novel desulfurizer that could meet the requirements of industrial flue gas regarding denitration under low temperature and complete desulfurization operation under dry conditions.

Experimental

Preparation of desulfurizer

The steam jet mill (shown in Figure 1) was employed for the digestion and preparation of high-efficiency calcium-based desulfurizer, from my previous research (Lū et al., 2020). Calcium-based desulfurizer was prepared under experimental conditions of 0.5 MPa steam pressure, the classifier speed and temperature were $2700 \text{ r}\cdot\text{min}^{-1}$ and $260 \text{ }^\circ\text{C}$, which was termed as 0[#] desulfurizer, whose particle size was $D_{10}=0.574 \text{ }\mu\text{m}$, $D_{50}=1.331 \text{ }\mu\text{m}$, $D_{90}=6.775 \text{ }\mu\text{m}$, a bulk density of $0.2134 \text{ g}\cdot\text{cm}^{-3}$, a specific surface area of $24.253 \text{ m}^2\cdot\text{g}^{-1}$ and digestion rate could reach 100%. As depicted in SEM, XRD, and size report (detail in Figure 2), 0[#] desulfurizer was characterized by the uniform distribution of particles, a honeycomb surface, and an obvious loose porous structure.

The ordinary calcium-based desulfurizer prepared by the traditional digestion best method was termed as 1[#] desulfurizer under specific conditions (at $95 \text{ }^\circ\text{C}$ for digestion, water-cement ratio (mass ratio) of 0.84:1, the stirring speed of $100 \text{ r}\cdot\text{min}^{-1}$, and 10 min digestion), whose bulk density and specific surface area were $0.496 \text{ g}\cdot\text{cm}^{-3}$ and $19.02 \text{ m}^2\cdot\text{g}^{-1}$. Based on the analysis of particle size, XRD, and SEM of 1[#] desulfurizer, as shown in Figure 3, the particle size of the desulfurizer was $D_{10}=0.742 \text{ }\mu\text{m}$, $D_{50}=4.901 \text{ }\mu\text{m}$, $D_{90}=39.260 \text{ }\mu\text{m}$, and additionally, it was observed with less uniform particle distribution, and more specifically, with some relatively large particles. Moreover, the particles displayed a dense and layered surface, and an irregular shape, and additionally, the particles were disorderly and gathered together to form irregular aggregates.

The NaHCO_3 provided by a coal chemical plant in Sichuan was used as the sodium-based desulfurizer, defined as 2[#] desulfurizer. The specific surface area of the desulfurizer was tested to be $1.021 \text{ m}^2\cdot\text{g}^{-1}$, bulk density of $0.8429 \text{ g}\cdot\text{cm}^{-3}$, and according to the investigation into particle size, SEM, and other apparent characteristics of the desulfurizer, as depicted in Figure 4, it could be understood that the particle size of 2[#] desulfurizer particles was $D_{10}=3.216 \text{ }\mu\text{m}$, $D_{50}=13.178 \text{ }\mu\text{m}$, $D_{90}=33.465 \text{ }\mu\text{m}$, and additionally, the cylindrical particles were overall less uniformly distributed with the existence of some relatively large ones and were disorderly aggregated.

Compared with 1[#] and 2[#] desulfurizers, 0[#] desulfurizer was discovered with smaller particle sizes. To ensure the accuracy and consistency of the experiment, the LNJ-240A air jet mill (Mianyang Liuneng Powder Equipment Co., Ltd., shown in Figure 5) was utilized for pulverization of 1[#] and 2[#] desulfurizers to obtain a desulfurizer with same particle size with 0[#] desulfurizer.

Under the pressure of 0.8 MPa and with the rotating speed of the particle classifiers at $3600 \text{ r}\cdot\text{min}^{-1}$, 1[#] desulfurizer was pulverized by the jet mill into 1-1[#] desulfurizer, and additionally, the particle size and SEM of 1-1[#] desulfurizer were analyzed, as shown in Figure 6 (the existence of large particles in 1[#] desulfurizer sample required the utilization of Ethylene Diamine Tetraacetic Acid (EDTA) titration method for calculation of the content of calcium oxide and CaO digestibility to avoid the error of XRD results). The particle size of 1-1[#] desulfurizer was $D_{10}=0.644 \text{ }\mu\text{m}$, $D_{50}=1.357 \text{ }\mu\text{m}$, $D_{90}=7.973 \text{ }\mu\text{m}$, and 85% digestibility and relatively uniform particle distribution were also observed. However, the surface structure

was still relatively dense, and meanwhile, calcium oxide substances with a dense hexagonal structure were wrapped in the interior, resulting from exposure of incompletely decomposed calcium oxide on the outer surface under the action of the high-speed airflow. The specific surface area of the desulfurizer was tested to be $21.39 \text{ m}^2 \cdot \text{g}^{-1}$, bulk density of $0.1780 \text{ g} \cdot \text{cm}^{-3}$, and the overall apparent performance of the particles was significantly improved after pulverization.

2-1[#] desulfurizer, prepared by pulverization of 2[#] desulfurizer under the same parameters, size, and SEM of 2-1[#] desulfurizer were analyzed, as shown in Figure 7. Its particle size was $D_{10}=0.612 \text{ }\mu\text{m}$, $D_{50}=1.578 \text{ }\mu\text{m}$, $D_{90}=7.920 \text{ }\mu\text{m}$, and notably high purity of NaHCO_3 and relatively uniform distribution of particles were discovered. However, the cylindrical powder was split in response to high-speed airflow, and the clearance among particles was smoothed into a flocculent structure. The specific surface area and bulk density of the desulfurizer were $3.594 \text{ m}^2 \cdot \text{g}^{-1}$ and $0.1811 \text{ g} \cdot \text{cm}^{-3}$, and different improvements would be determined relative to that before pulverization.

Experiment apparatus

The desulfurization performances were compared in the DFGD testbed. The experimental device for DFGD is shown in Figure 8, which is mainly composed of five parts: 1) simulated gas source, mainly includes the O_2 , SO_2 , N_2 , cylinders. 2) Flue gas measuring system, a flue gas analyzer is used to test the concentration of SO_2 (mainly inlet and outlet concentration of SO_2). 3) Flue gas pretreatment system, including the experimental gas mixer, piping, insulation, water pump, and steam generator. 4) The reaction assembly, including the experimental flue gas reactor (a quartz tube, a length of 1200 mm and internal diameter of 25 mm) and fixed bed combustion. 5) The title tail gas treating unit (TGTU), with NaOH aqueous solution to remove SO_2 from the exhausted flue gas.

Experimental parameters and methods

a 5.00 g of the desulfurizer was placed in the flue gas reactor of each group. The reaction assembly temperature was $150 \text{ }^\circ\text{C}$ and the flue gas flow was $700 \text{ mL} \cdot \text{min}^{-1}$. The flow rate of the pump was adjusted to ensure the relative humidity in the fixed bed combustion. And the relative humidity was adjusted to 12%.

The SO_2 data was calendared at the outlet of the flue gas reactor (C_t) every 20 minutes to acquire the relationship curve between the working time and SO_2 outlet concentration under different humidity conditions. During these experiments, the initial SO_2 concentration was maintained at $850 \text{ mg} \cdot \text{m}^{-3}$. The desulfurization breakthrough of the flue gas reactor is detected to be more than 70% of the initial SO_2 concentration (C_0) when passing through the reactor, therefore when an SO_2 concentration higher than $200 \text{ mg} \cdot \text{m}^{-3}$ was measured, the reactor will be deemed to be in a "breakthrough" status. Similarly, the

working time required for the reactor to reach the "breakthrough" state is regarded as the breakthrough time of the reactor.

The desulfurization performance is evaluated by calculating the desulfurization efficiency of the desulfurizer. The formula for calculating the desulfurization efficiency F of the desulfurizer is as follows:

$$F = \frac{C_0 - C_t}{C_0} \quad (1)$$

Where F indicates the desulfurization efficiency, C_0 represents the inlet concentration and C_t shows the outlet concentration of SO_2 at working time t .

Results And Discussion

Desulfurization performance

It could be seen from Figure 9 that with the increase of the desulfurization time, the SO_2 outlet concentration remained stable and then displayed a rapid augment, while the desulfurization efficiency kept stable first and then rapidly declined, indicating that desulfurizers could quickly fail after a period of operation. Under the circumstances of the same SO_2 outlet concentration or the same desulfurization efficiency, the breakthrough of effect for 0[#] desulfurizer lasted the longest time, namely 460 min, followed by 2-1[#] desulfurizer, 1-1[#] desulfurizer, 2[#] desulfurizer, and 1[#] desulfurizer, and the breakthrough time of 1-1[#] desulfurizer and 2-1[#] desulfurizer was 180 min and 400 min, respectively, much longer than that of 1[#] desulfurizer and 2[#] desulfurizer. It was herein suggested that the apparent properties of the superfine desulfurizer were significantly improved, and the desulfurization efficiency increased rapidly. Additionally, it was displayed that 1[#] desulfurizer cannot maintain 100% desulfurization efficiency, while the efficiency of 1-1[#] desulfurizer was also lower than 100% in the initial stage of 0-40 min. As the desulfurization continued, the desulfurization efficiency reached 100% during 40 to 120 min, mirroring the second digestion of 1-1[#] desulfurizer in the initial stage of desulfurization under favorable reaction conditions provided by desulfurization circumstances. More importantly, further digestion strengthened the activity of the desulfurizer and its efficiency rapidly increased to 100%. Based on a performance comparison among the 5 desulfurizers, high-performance calcium-based desulfurizer was verified to be superior to sodium-based desulfurizers represented by NaHCO_3 with similar particle size.

It has been generally recognized through experimental analysis that the desulfurization performance of traditional calcium-based desulfurizers is lower than that of sodium-based desulfurizers, and from previous literature (Ahmed et al., 2021; Min et al., 2010), as a result, to meet industrial SO_2 emission standards, the calcium-sulfur ratio of calcium-based desulfurizers were 5:1~10:1, while that of sodium-based desulfurizers was only 1.3:1 to 1.6:1. Low desulfurization efficiency resulted in less frequent

utilization of such desulfurizers, and calcium-based desulfurizer was not considered an option in dry desulfurization. However, the intensive processing of traditional calcium-based desulfurizers in this project contributed to its higher desulfurizer efficiency relative to sodium-based desulfurizers under the same desulfurization conditions, which broke through the conventional cognition and would significantly contribute to augmented efficiency of calcium-based desulfurizers in dry flue gas desulfurization.

Instead of the traditional digestion process of calcium-based desulfurizers, a steam jet mill with superheated steam as the pulverizing medium was employed in the present study for pulverization and quicklime digestion to prepare high-efficiency calcium-based desulfurizer which displayed overtly advantageous apparent properties including specific surface area and desulfurization performance in comparison to sodium-based desulfurizers. Additionally, effective advancements in apparent characteristics of particles and desulfurization performance could be achieved after pulverization of desulfurizers with the help of the jet mill with compressed air at normal temperature as the medium. Therefore, a steam jet mill or jet mill could contribute to the creation of novel processes to promote desulfurization performance, which is of significant importance in the promotion and application of dry flue gas desulfurization technology.

Heating characteristics

At an initial desulfurization temperature of 100 °C and up-regulation of 20 °C every 10 min, the correlation between desulfurization efficiency and temperatures of the different types of desulfurizers was investigated, as shown in Figure 10.

As depicted in Figure 10, the continuous increment in the temperature resulted in a gradual increase in SO₂ outlet concentration but a decline in desulfurization efficiency, suggesting that temperature negatively modulated the efficiency of desulfurizers. The desulfurization efficiency of 1[#] desulfurizer could reach over 70% at 100 °C to 160 °C, and dropped to only 56.47% at 180 °C, reflecting that the critical temperature of 1[#] desulfurizer was 160 °C. As for 1-1[#] desulfurizer, 100% efficiency could be maintained when the temperature was increased from 100 °C to 140 °C, and the desulfurization efficiency dropped to 81.65% at 200 °C and rapidly decreased to 46.82% at 220 °C, from which the critical temperature for 1-1[#] desulfurizer was suggested to be 200 °C. Similarly, it was indicated from Figure 10 that the critical temperature for 2[#] desulfurizer and 2-1[#] desulfurizer was 180 °C and 200 °C, respectively. Based on desulfurization characteristics with temperature augment among 1[#], 1-1[#], 2[#], and 2-2[#] desulfurizers, we could conclude that the critical temperature at which desulfurization efficiency rapidly declined did not exceed 200 °C. In other words, ordinary calcium-based desulfurizers and sodium-based desulfurizers cannot realize high-efficiency desulfurization under conditions higher than 200 °C.

For 0[#] desulfurizer, it was testified in Figure 10 that 100% desulfurization could be maintained with the desulfurizer temperature increased from 100 °C to 240 °C. And with the temperature rising to 260 °C and then 280 °C, the desulfurization efficiency dropped slightly to 96.23% and obviously to 61.76%

separately. It was indicated that the critical temperature inducing the rapid decrease of desulfurization efficiency of 0[#] desulfurizer was 260 °C, and more importantly, the applicable high-efficiency desulfurization temperature of 0[#] desulfurizer was higher than that of the above four desulfurizers.

According to the results of desulfurization characteristics with temperature increases, the applicable high-efficiency desulfurization temperature of the desulfurizer after jet mill pulverization was higher than that before pulverization, but the difference was not obvious. Additionally, high-efficiency calcium-based desulfurizer, as compared with ordinary calcium-based desulfurizers and sodium-based desulfurizers, could desulfurize at wider applicable temperatures, and achieve more desulfurization efficiency at the same temperature. Currently, in the industrial integrated flue gas desulfurization and denitration process, the denitration temperature generally should be maintained up to 200 °C for higher activity of the denitration catalysts, and the high-efficiency calcium-based desulfurizer could be applied without affecting desulfurization efficiency but with the flue gas temperature controlled at 200 °C to 260 °C, which can not only meet the high desulfurization efficiency but also provide suitable reaction conditions for the catalysts in the denitration process.

Energy consumption analysis of desulfurizer preparation capacity

1[#] desulfurizer was prepared after full digestion of quicklime via a digester in a simple process. The production cost mainly included the cost of quicklime raw material and that of digestion. The quicklime was about 300 $\text{t}\cdot\text{T}^{-1}$ and high-temperature water was utilized for digestion (Ding et al., 2019), in which the water-cement ratio was 0.84:1, cost roughly 50 to 100 $\text{t}\cdot\text{T}^{-1}$, and taken together, the production cost of 1[#] desulfurizer was about 342 to 384 $\text{t}\cdot\text{T}^{-1}$. 2[#] desulfurizer could be purchased directly at the price of roughly 2000 $\text{t}\cdot\text{T}^{-1}$.

1-1[#] desulfurizer and 2-1[#] desulfurizer required pulverization utilizing a jet mill. The LNJ-240A air jet mill was applied for pulverization of the two desulfurizers to facilitate the calculation of industrial production. The main parameters of the LNJ-240A air jet mill were shown in Table 1. The rated power was 272 kW, and the actual energy consumption was 231.7 $\text{Kw}\cdot\text{h}^{-1}$. The processing capacity of 1-1[#] desulfurizer was 320 $\text{Kg}\cdot\text{h}^{-1}$, that is, the total power consumption for the production of 1 ton of 1-1[#] desulfurizer material was 724.06 $\text{Kwh}\cdot\text{T}^{-1}$, and the total cost was 1024.06 t . Similarly, the output of 2-1[#] desulfurizer was 280 $\text{Kg}\cdot\text{h}^{-1}$. In other words, the total power consumption of manufacturing 1 ton of 2-1[#] desulfurizer material was 827.5 $\text{Kwh}\cdot\text{T}^{-1}$ and the total cost price was 2827.5 $\text{t}\cdot\text{T}^{-1}$.

0[#] desulfurizer was prepared by pulverizing and digesting quicklime through a steam jet mill, whose parameters were shown in Table 1. The rated power was 7.5 kW, and the actual energy consumption was 6 $\text{Kw}\cdot\text{h}^{-1}$. The output was 60.5 $\text{Kg}\cdot\text{h}^{-1}$, that is, production of 1 ton of 0[#] desulfurization consumed 99.17 $\text{Kwh}\cdot\text{T}^{-1}$ of power. Also, superheated steam was utilized as the pulverizing medium for the LNGS-80 steam jet mill. 72 $\text{Kg}\cdot\text{h}^{-1}$ of system steam consumption needed to be taken into consideration and the

production of 1 ton of material required 667 Kg of steam. The cost of superheated steam was $200 \text{ ¥} \cdot \text{T}^{-1}$, so 133.4 ¥ was spent on the steam. Therefore, considering the cost of raw materials, power consumption, and steam, the cost of producing 1 ton of 0[#] desulfurizer was about 532.57 ¥.

According to current market circulation prices, the processing and preparation costs of different desulfurizers were analyzed. In the production of desulfurizer per unit mass, the cost of 1[#] desulfurizer was the lowest, followed by 0[#], 1-1[#], 2[#], and 2-1[#] (the highest). Based on a comparative analysis of desulfurizers with higher efficiency, namely 0[#] and 2-1[#] desulfurizers, the production cost of the sodium-based desulfurizer after pulverization was about 5.36 times higher than that of the high-efficiency calcium-based desulfurizer. After 1 T of the flue, gas SO₂ was removed through theoretical calculations, 1.156 tons of high-efficiency calcium-based desulfurizer were required at the price of 615.65 ¥, while 1.312 tons of pulverized sodium-based desulfurizer were needed at the price of 3,709.68 ¥, which was 6.02 times higher than that of high-efficiency calcium-based desulfurizer.

Ecological environment pollution has become the focus worldwide, and under such circumstances (Yi et al., 2008; Pan et al., 2019), in response to national policies on energy conservation and emission reduction, energy structure adjustment, carbon neutrality, and peaking carbon dioxide emissions, the industrial application of waste heat from industrial emissions which could be fully utilized to provide pulverization energy for steam jet mills, to a certain extent, is expected to further reduce the cost of desulfurization. As for the high-performance characteristics of high-performance calcium-based desulfurizers, the authors will further analyze and study them. Therefore, this technology, in which a steam jet mill is applied for quicklime digestion to prepare high-performance calcium-based desulfurizers, could realize relatively high desulfurization efficiency, and accordingly has great development potential in the field of flue gas desulfurization.

Conclusions

1. When the SO₂ concentration is $850 \text{ mg} \cdot \text{m}^{-3}$ and the desulfurization temperature is 150 °C, the high-performance calcium-based desulfurizers, ordinary calcium-based desulfurizers, ultra-fine ordinary calcium-based desulfurizers, Na-based desulfurizers, and ultra-fine Na-based desulfurizers the “break-through” time is 460, 80, 180, 120, and 400 min. The SJM desulfurizer with 100% desulfurization efficiency for the longest time, up to 420 min.
2. Pulverization could result in an overt increment in effective desulfurization time of sodium-based and calcium-based desulfurizers. Conventional sodium-based and calcium-based desulfurizers could not desulfurize effectively at 200 °C before or after pulverization, while high-performance calcium-based desulfurizers could display highly effective desulfurization under temperature as high as 260 °C. Under such circumstances, not only relatively high effectiveness of desulfurization could be achieved, but also a suitable temperature could be provided for the integrated denitration process.
3. Compared with conventional sodium-based desulfurizer, high-performance calcium-based desulfurizer prepared after quicklime digestion with the help of a steam jet mill is characterized by

several advantages, including high desulfurization efficiency, wider applicable desulfurization temperatures, and lower energy consumption, allowing for significant development potential in the field of flue gas desulfurization.

Declarations

Authors Contributions

Juan Lū: Data curation, Formal analysis, Project administration, Writing, Investigation. Yu Fu: Investigation, Reviewing, Data Curation, Visualization. Jianbo Wang: Reviewing, Data Curation, Resources. Haiyan Chen: Data curation, Formal analysis, Project administration, Supervision, Funding acquisition. All authors read and approved the final manuscript.

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Data Availability

The datasets used and analyzed during the current study are available from the corresponding author upon request

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Competing interests The authors declare no competing interests.

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Table

Table 1 Technical parameters of air jet mill and steam jet mill

Parameters	LNGS-80	LNJ-240A	
Gas parameters	Steam, 0.45 MPa, 150~300 °C	25 °C, 0.8 MPa	
Draught fan power	4.5 kW	30 kW	
Classifier power	3 kW	22 kW	
Air compressor		220 Kw	
Rated Total power	7.5 kW	272 Kw	
Actual powder	6 Kw•h	231.7 Kw•h	
Capacity	60.5 Kg•h ⁻¹	320 Kg•h ⁻¹	280 Kg•h ⁻¹
Power consumption per ton	99.17 Kwh•T ⁻¹	724.06 Kwh•T ⁻¹	827.5Kwh•T ⁻¹
Power all cost, 1RMB /Kw.h	99.17 ¥•T ⁻¹	724.06 ¥•T ⁻¹	827.5 ¥•T ⁻¹
Steam cost=200¥/T	133.4 ¥•T ⁻¹	/	/
Steam cost=100¥/T	66.7 ¥•T ⁻¹	/	/
Preparation cost/¥•T ⁻¹	532.57	1024.06	2827.5

Figures

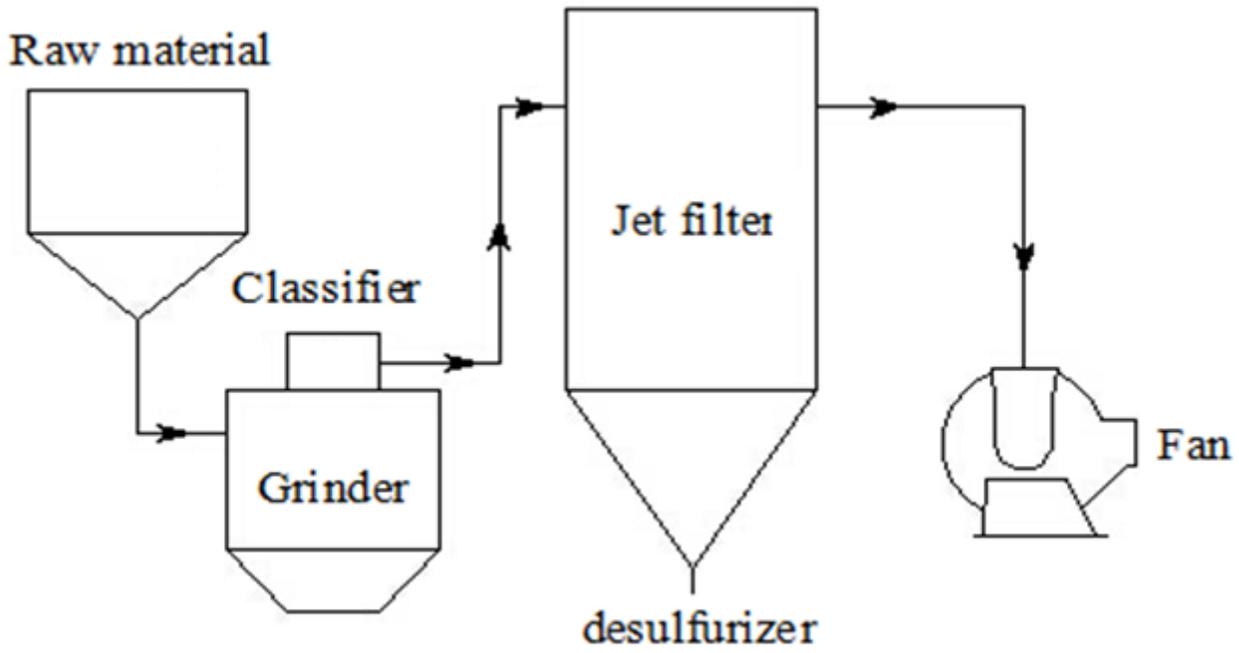


Figure 1

LNGS-80 steam jet milling system.

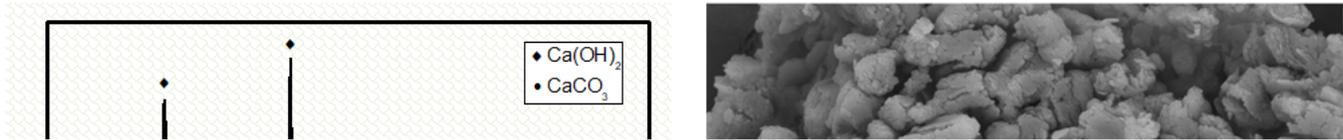


Figure 2

The apparent characteristics of SEM and XRD of high-performance desulfurizer.

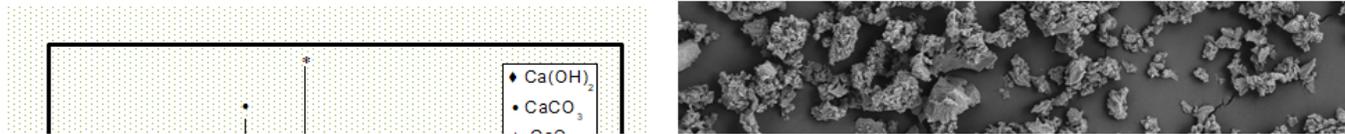


Figure 3

Particle size, SEM, and XRD patterns of 1[#] Ca-based desulfurizers.

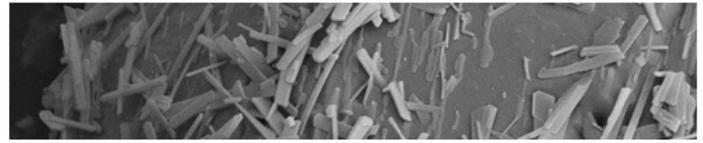


Figure 4

Particle size, SEM, and XRD patterns of 2[#] Na-based desulfurizers.

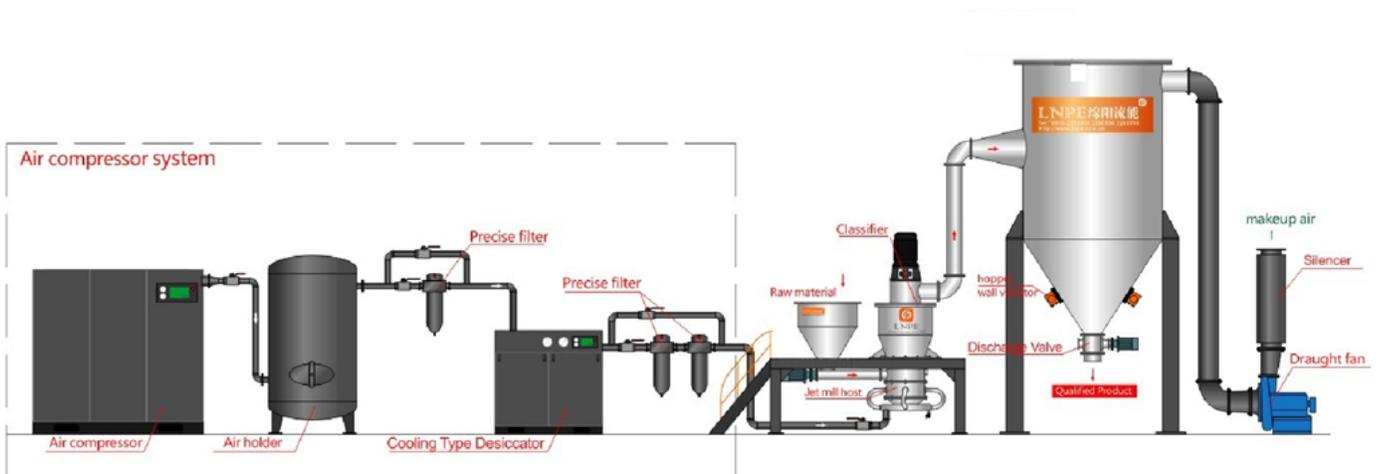


Figure 5

LNJ-240A air jet mill system.

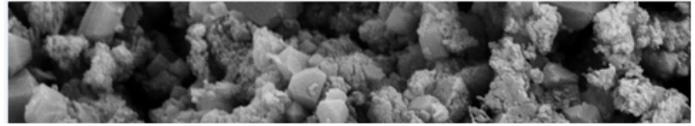


Figure 6

SEM and size reports of 1-1# calcium-based desulfurizers.

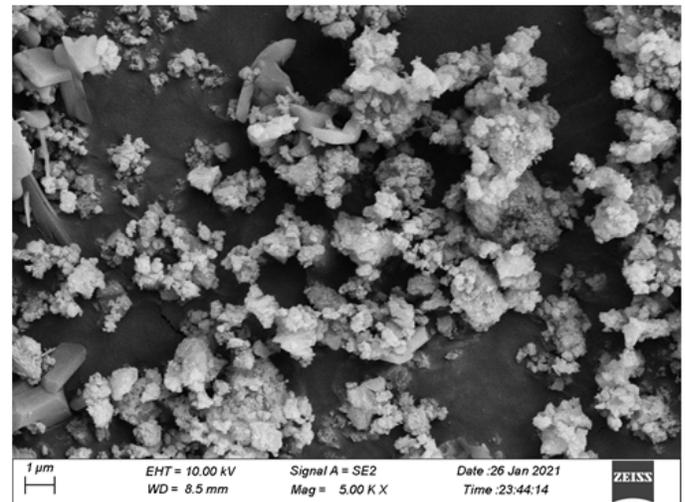
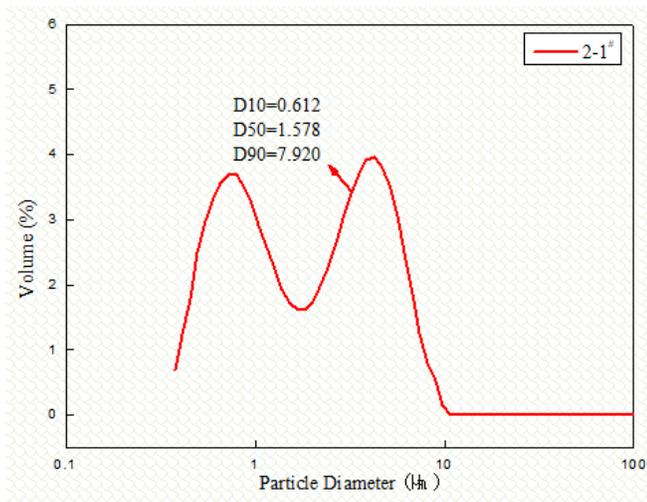


Figure 7

SEM and size reports of 2-1# Na-based desulfurizers.

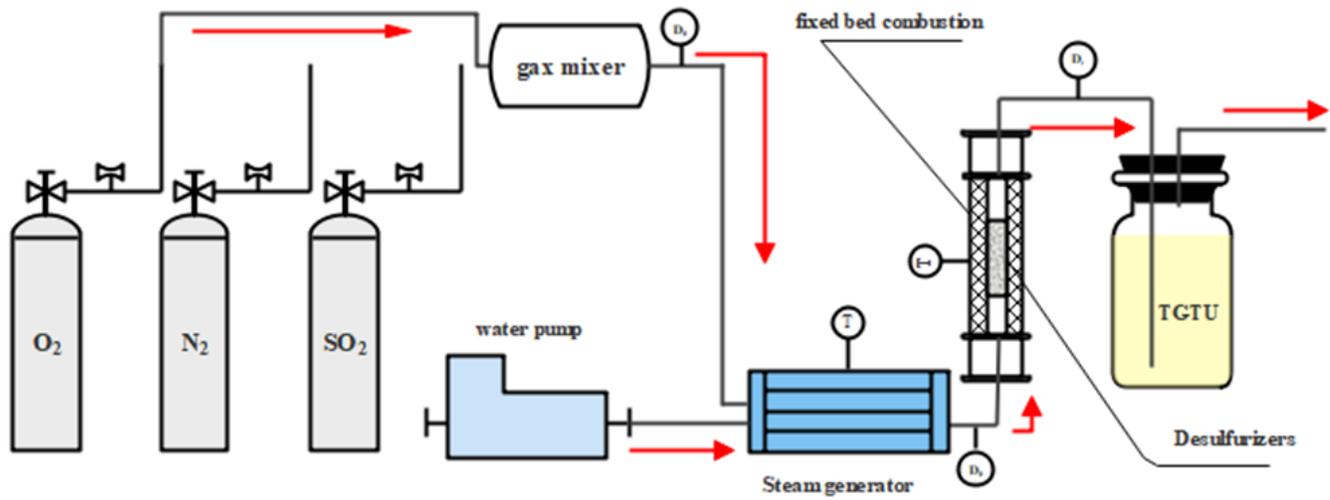


Figure 8

Schematic diagram of the experimental arrangement for desulfurization.

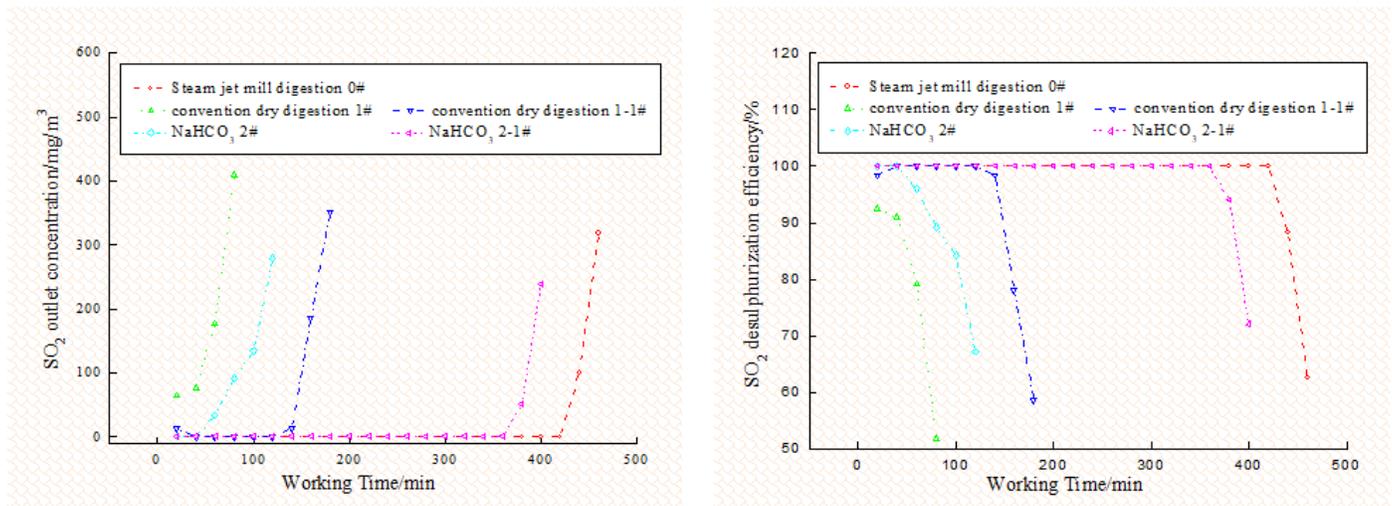


Figure 9

Desulfurization efficiency and outlet concentration of desulfurizers at different working times.

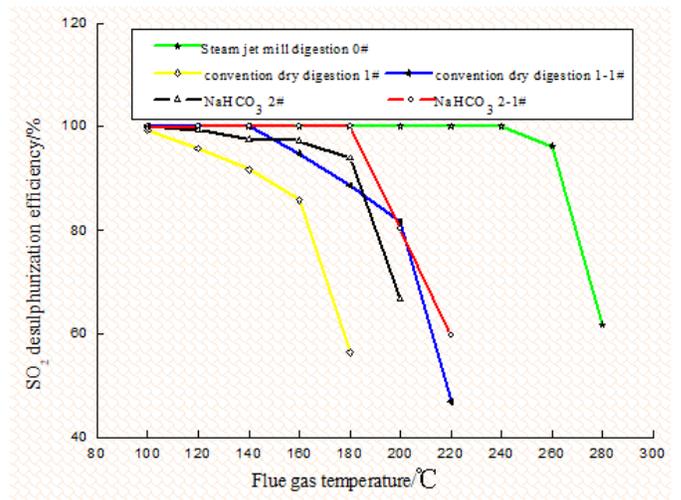
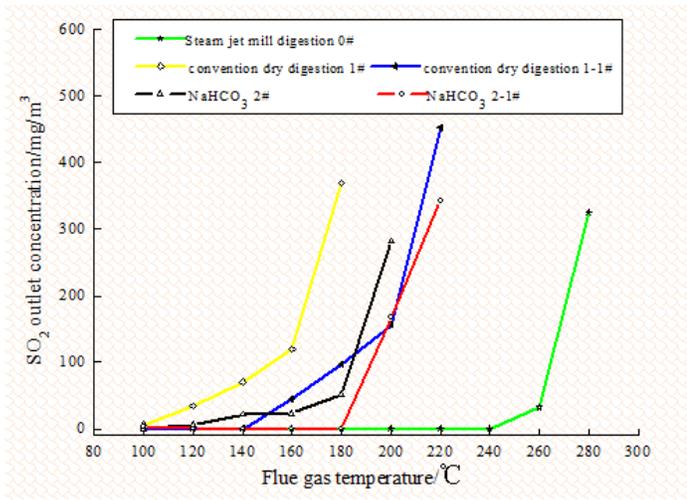


Figure 10

Desulfurization concentration and desulfurization efficiency of desulfurizers at different temperatures.