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During the Water Crisis, Coal-Fired Power Plants Use Membrane Distillation Technology to Treat Wastewater

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Abstract

The contradiction between the current situation of water shortage and the high-water consumption, high sewage discharge of coal-fired power plants is an urgent problem that needs to be improved in the traditional wastewater treatment process. As a new separation technology with high efficiency and energy saving, membrane distillation technology shows unique advantages in treating high-salt desulfurization wastewater. Based on this, this paper systematically sorts out China's current situation in terms of water resources and the typical wastewater treatment process of coal-fired power plants today. Four membrane distillation technologies are analyzed: Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (GMD), Vacuum Membrane Distillation (VMD), Sweeping Gas Membrane Distillation (SGMD), with their rationale and potential in desulfurization wastewater treatment. The results show that membrane distillation technology can achieve near-zero discharge and high quality of the produced water, the recovery rate can reach more than 90%. However, there are still uncertainties and performance differences in actual power plant applications. Membrane distillation technology also faces membrane pollution, high energy consumption, poor long-term operation stability, etc. Future work should focus on development and development of high-performance materials, optimize not only the integrated system but operation strategy. What's more, vigorously promotes the application of membrane distillation technology in wastewater treatment of coal-fired power plants to help power plants achieve efficient water resource recycling and green and low-carbon transformation.

Keywords

water resources, coal-fired power plants, wastewater treatment, membrane distillation technology

1. Introduction

The rapid development of the economy and technology has brought many opportunities to the country and society, but also brought many challenges. According to statistics, China's per capita water resources share is 1757.9m*3/person, which is only 1/4 of the world average. Facing serious water shortages and pollution problems (National Bureau of Statistics, 2023). China's total water consumption in 2022 will be 599.82 billion m*3, of which industrial water accounts for about 16% (Ministry of Water Resources of the People's Republic of China, 2022).In China's industrial development, thermal power plants consume a huge amount of water, accounting for about 11% of the total industrial water consumption (Ministry of Water Resources of the People's Republic of China, 2022). Scientific, rational, and efficient recycling and treatment of power plant wastewater is crucial to alleviating water resource shortages and protecting the ecological environment.

As a new separation technology, membrane distillation technology has the advantages of high separation efficiency, low temperature requirements, simple and easy maintenance equipment, and high effluent standards. It has significant advantages in industrial wastewater treatment. Lee et al. used raw flue gas desulfurization wastewater obtained from a coal-fired power plant in South Korea and used forward osmosis (FO) and membrane distillation (MD) to treat flue gas desulfurization (FGD) wastewater, and found that MD can reconcentrate the diluted scale inhibitor blended stretch solution (DS) to a recovery rate of 50% and maintain the flux in a relatively stable state (Lee et al., 2018). Carmela et al. used an integrated membrane process that included chemical softening and ultrafiltration (UF) to remove Ca2+ and Mg2+ ions as well as organic compounds, and the integrated system they studied resulted in a total recovery of approximately 94% and produced an MD osmotic stream with a conductivity of 80 S/cm (Conidi et al., 2018). Jia et al. used nanofiltration membrane distillation integration (NF-MD) technology to study the treatment process of flue gas desulfurization (FGD) wastewater, successfully achieved near-zero liquid discharge, and the whole system could achieve a salt discardment rate of more than 99.99% with a reclaimed water rate of higher than 92% (Jia and Wang, 2018). However, there are many differences in the performance of different membrane distillation technologies in treating desulfurization wastewater from thermal power plants (Liu et al., 2023).

Based on the current situation of water resources, this paper analyzes the wastewater treatment of coal-fired power plants and discusses the research on membrane distillation technology, aiming to find a more efficient, clean, and environmentally friendly wastewater treatment method.

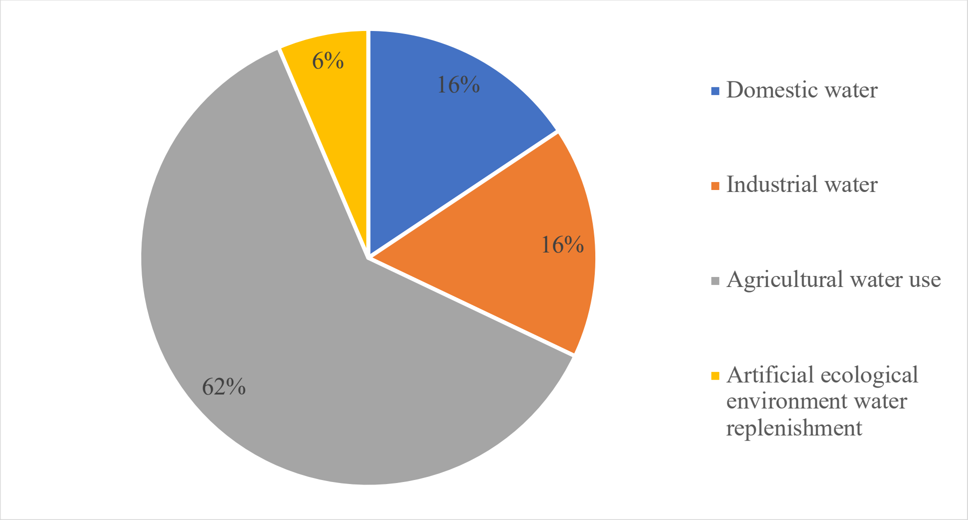
2. China’s Water Resources

Water resources refer to water sources that are available or likely to be used. Water, which is currently and recently available to humans directly or indirectly, occupies an important place in the composition of natural resources. Natural water resources include: river and their runoff, groundwater, snow and glaciers, lakes, and swamp water. In addition, seawater is also a part that cannot be ignored. According to water quality, it is divided into freshwater and saltwater.

In 2024, China’s annual precipitation will be 717.7mm, 11.4% more than the multi-year average. This is an increase of 11.6% from 2023, ranking third in China’s annual precipitation series since 1956, after 1998 and 2016 (Ministry of Water Resources of the People's Republic of China, 2024). In 2024, China’s total water resources will be 3,112.30 billion m*3, 12.7% more than the multi-year average. China’s total water resources account for 45.8% of the total precipitation (Ministry of Water Resources of the People's Republic of China, 2024).

In 2024, China’s total water consumption will be 592.80 billion m*3, of which domestic water consumption will be 92.68 billion m*3, accounting for 15.6% of the total water consumption; industrial water consumption was 97.10 billion m*3, accounting for 16.4% of the total water consumption; The 364.84 billion m*3 is agricultural water consumption, accounting for the vast majority of total water consumption, reaching 61.6%;The water replenishment of the artificial ecological environment was 38.18 billion m*3, accounting for 6.4% of the total water use (Lee et al., 2018). Industrial water is second only to agricultural water in terms of water consumption, as shown in Figure 1.

Figure 1: The Proportion of water resources utilization (Photo/Picture credit: Original)



The 2,100 cubic meters is the share of Chinese's per capita water resources, 28% of the world's per capita level, which is only the statistics of 2020 data. At present, about 60% of China's cities are in urgent need of water resources, and about a quarter of cities are severely short of water. Finding efficient water treatment and recycling technologies is urgent (Lee et al., 2018).

3. Current Status of Wastewater Treatment in Coal-Fired Power Plants

For the treatment of wastewater after desulfurization of thermal power plants, there are many mature solutions on the market. Table 1 provides a detailed analysis of the specific processes of desulfurization wastewater treatment in representative power plants in the world (Liu et al., 2023).

Table 1. Comparison of zero discharge process routes and advantages and disadvantages of desulfurization wastewater

Company name	Process route	Process advantages	Process disadvantages
Weiya Company (Yang, 2019)	Ion exchange/chemical softening pretreatment + (seed) falling film evaporator + MED	The high-quality distillate in the produced water can be used multiple times in power plants, and the maximum TDS in the circulating water is less than $2\times^{10\text{-}5mg/L.}$	Chemical softening and hardening, and subsequent evaporation, require the addition of the seed method.
Australian Energy Resources (Wang, 2021)	Softening + MVR + crystallization	The effluent TDS is less than 20mg/L	The amount of water intake is large
Guodian Hanchuan Power Plant (Wan et al., 2017, Xu et al., 2020)	Double base method + integrated tubular ultrafiltration membrane (TUF) + NF + special flow channel reverse osmosis membrane (SCRO) + DTRO + MVR	The effluent quality is good, and the freshwater recovery rate is 93.4%. After pretreatment, the concentration of calcium and magnesium ions in water can be reduced to less than 2 mg/L. The water consumption of the entire system was reduced to 280,000 t/a, and the solid waste discharge was reduced by nearly 7,000 t/a. NaCl purity above 98.60%	long process, complex equipment, large footprint; The amount of pretreatment dosage is large, the amount of sludge produced is large, and the softening cost is high. The adaptability of membrane concentration components to water quality fluctuations is poor, and the TUF pollution plugging rate is high. The running cost is high.

Company name	Process route	Process advantages	Process disadvantages
Huadian Baotou Power Plant (Li, 2020, Sun and Shen, 2018)	Pretreatment +NF+RO+DTRO+MVR	The recovery rate of freshwater is 50%-55%; Na_2SO_4 and NaCl can be recovered separately. The electricity consumption is 60 kW·h/t, the cost per ton of water is 1.08 million yuan, and the cost of operation is low	large water intake; The pretreatment dosage is large, and the softening cost is high; RO film is prone to contamination, concentration polarization, and scaling
Miki Hengyi Power Plant (Sun and Shen, 2018, Liu, 2014)	Conventional pretreatment + two-stage horizontal spraying/MVC + two-stage horizontal MED + horizontal four-disc frosting	The energy consumption is low, the consumption of steam is 50~60kg/t, the electricity consumption is 20~25Kw·h/t, and the cost per ton of water is 3 million yuan	The water quality has not been softened, and the scale is serious; The crystalline salt contains heavy metals that cannot be used efficiently, and the processing cost is high.

Some typical methods of treating wastewater in coal-fired power plants are given below.

The traditional physical and chemical pretreatment process with the ‘triple box’ as the core is currently the first choice for most power plants in China. The technical device is shown in Figure 1. This technology is mature and stable, can effectively remove a large amount of heavy metals and suspended substances from wastewater, and has low investment and operating costs. The following is a brief introduction to the technical principle of the ‘triple box’.

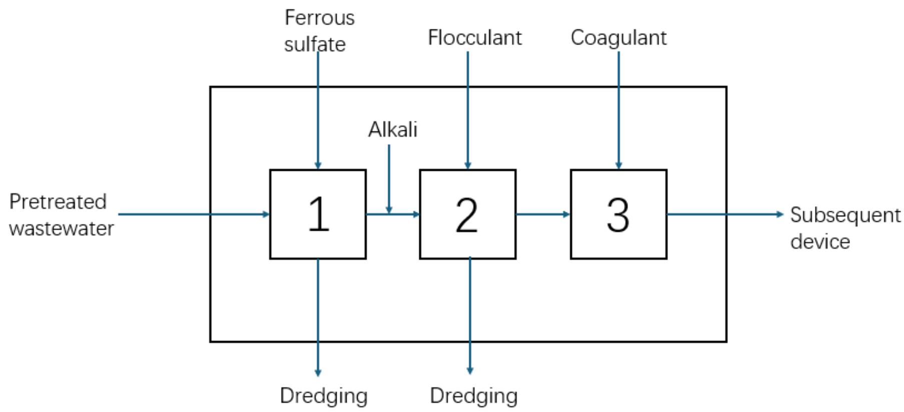
The first box is the pH adjustment chamber (neutralization box), where the acid-base neutralization reaction of wastewater occurs. Power plant wastewater (especially wet desulfurization wastewater) is usually acidic and rich in a different classes of heavy metal ions (such as Cu, Pb, Zn, Cr, etc.).This process can accurately control the pH value of wastewater to the alkaline range (usually 9-10.5) by adding alkaline agents (such as NaOH, $Ca(OH)_2$, etc.).

The second box is the reaction tank (flocculation box), where the wastewater coalesces and flocculates. After neutralization, a large number of tiny heavy metal hydroxide colloidal particles are formed in the water, which are difficult to settle naturally because they are difficult to repel each other with the same charge. In this link, coagulants (such as iron salts, aluminum salts) and flocculants (such as PAM) need to be added to accelerate flocculation.

The last box is the sedimentation chamber (clarification box), which uses gravity for sedimentation separation. Wastewater containing a large amount of alum flocculants is fed into the sedimentation tank to slow down the flow of water.

However, because the method cannot remove chloride ions and dissolved total solids from wastewater, the utilization rate of treated wastewater is low, and the application is limited to dry ash humidity regulation and coal yard spraying, so it is urgent to optimize the depth of regulation.

Figure 2: Schematic diagram of the physical and chemical pretreatment process device of the triple box



Due to earlier environmental protection measures and regulations, international technology routes are more inclined to thorough treatment and resource recycling, such as MVR evaporation and crystallization systems. In this system, the wastewater to be treated is first preheated to reduce energy consumption and enters the system, and then into the forced circulation heater. Here, the wastewater is heated by the high-temperature compressed steam of the MVR steam compressor, evaporating part of the water, then the gas-liquid and its mixture enter the crystallizer. The solution is steamed in this secondary steam; the salt begins to crystallize and precipitate. The discharged slurry enters the centrifuge for separation; the separated product is the final product. The remaining liquid (mother liquor) after separation is collected into the mother liquor tank, part of which is returned to the system to continue concentrating, and part of it is discharged as final wastewater. Evaporative crystallization systems are popular for their more stable and reliable indicators, but the high energy consumption, investment, and operating costs that come with them are always the number one problem for manufacturers.

4. Membrane Distillation Technology

Membrane distillation technology has shown unique advantages in industrial wastewater reuse, especially in treating wastewater with high salt and high concentration. Its nearly 100% retention rate enables true ‘zero liquid emissions ‘. It produces extremely high-quality produced water (distilled water grade), which can meet the high-end reuse water quality requirements, such as ultrapure water preparation and high-end cosmetics production. This has greatly improved the utilization rate of water resources and alleviate the current situation of water shortage. The following is an introduction to membrane distillation technology.

4.1 Principle of Membrane Distillation Technology

The liquid or hot side is the name often referred to by the side that is in direct contact with the liquid to be treated during membrane distillation, and the other side is called the osmosis side or cold side. Under the impetus of the vapor pressure difference, the hot side liquid is concentrated, and the cold side obtains pure water, so as to realize the separation or purification of the material liquid. The transfer process of water vapor in membrane distillation is mainly divided into three steps: first, water is devaporized near the membrane surface on the hot side, then water vapor enters the cold side through the membrane pores, and finally, water vapor condenses on the cold side of the membrane.

4.2 Types of Membrane Distillation Technology

4.2.1 Direct Contact Membrane Distillation (DCMD)

Direct contact membrane distillation directly contacts the hot material liquid on one side of the membrane and the cold fluid on the other side, relying on the temperature difference between the two sides of the membrane to form a vapor pressure difference, thereby driving the evaporation-condensation process. Its core feature is that the mass transfer and heat transfer paths are highly coupled, both of which can be carried out through the membrane. The advantage of DCMD is that it has a simple structure (as shown in Figure 3). It is easy to operate and has a large membrane flux, which is used in more than 60% of membrane distillation plants currently used in industry (Andrés-Mañas et al., 2018). However, due to its dependence on high temperatures to form vapor pressure differences, energy consumption is relatively high, and cooling water may be polluted in small amounts, resulting in high cost budgets.

4.2.2 Air Gap Membrane Distillation (AGMD)

The air gap membrane distillation provides an air gap between the membrane and the cold side, which increases the resistance to heat transfer and reduces the loss in the membrane distillation process. Due to the existence of air gaps, the membrane is not easy to be wetted by the permeate fluid, so it can be used to treat liquids containing volatile substances, as shown in Figure 4. Eryildiz et al. found that the boron removal rate was more than 99% when treating wastewater with three different boron concentrations (2598, 2795, and 6242 mg/L B) in the AGMD system (Eryildiz et al., 2021).AGMD has excellent development potential in the fields of separating volatile substances in aqueous solution, and the condensate plate is completely isolated from the material and liquid, so that the volatile parts can be efficiently recovered. However, the air gap will trap the air in the membrane pores and increase the mass transfer resistance of steam, so the membrane flux of AGMD is small.

4.2.3 Vacuum Membrane Distillation (VMD)

Air is pumped by a vacuum pump on the permeable side of the membrane and then distilled on the membrane, so that a large vapor pressure difference is generated on both sides of the membrane, which drives the water vapor in the material liquid to evaporate and pass through the membrane pores. Finally, the distillation is completed by condensation on the cold side. The structure of the device is shown in Fig. 5. The advantage is that it has a large mass transfer drive, resulting in a larger mass transfer flux, and VMD is more energy-efficient than DCMD (Sharan et al., 2022). The disadvantage is that VMD is more prone to membrane scaling and membrane pore wetting, which increases the cost of membrane cleaning and requires a vacuum system in distillation, which increases the cost of equipment.

4.2.4 Scavenging Membrane Distillation (SGMD)

The hot side of the scavenging membrane distillation membrane is usually treated at atmospheric pressure, and the steam generated during the evaporation of the material liquid is carried to the cold side for condensation by dry, low-temperature purge gas such as nitrogen (as shown in Figure 6). The advantage of SGMD is that it can be used to treat soluble or volatile gases in water. The disadvantage is that the purge gas needs to flow continuously during the distillation process, which has high energy consumption and is rarely used in industry (Chandra Bhoumick et al., 2023).

Figure 3. The structure of the DCMD

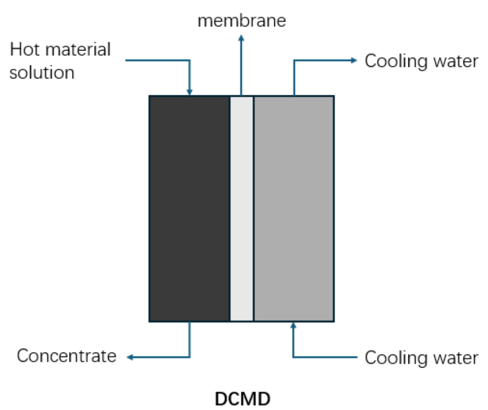


Figure 4. The structure of the AGMD

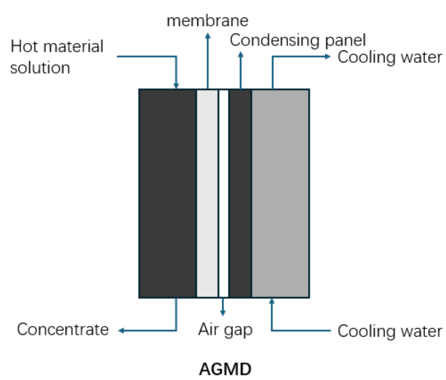


Figure 5. The structure of the VMD

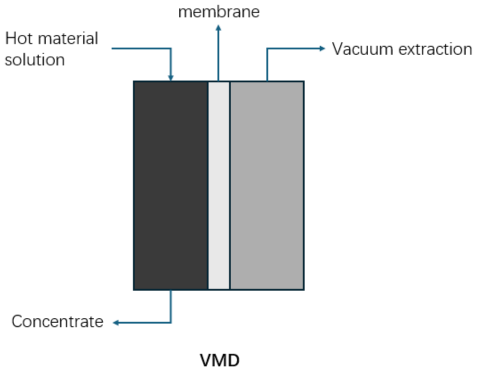
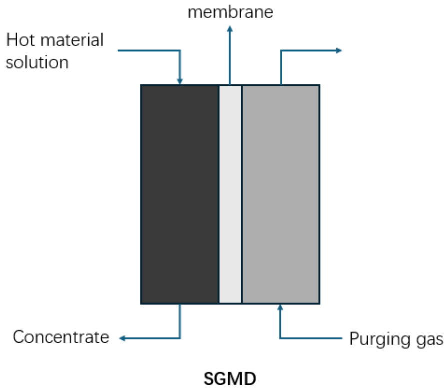


Figure 6. The structure of the SGMD



4.3 Conclusion

In the face of China's water shortage, high water consumption, and high emissions of coal-fired power plants, low water resource utilization rate, and low recovery efficiency. Power plants urgently need to change to less energy-efficient water treatment processes, such as traditional physical and chemical pretreatment with 'triple assembly' as the core. As an emerging water treatment technology, membrane distillation technology has the advantages of a nearly 100% salt interception rate, high salt wastewater can be treated, and high effluent quality. It can alleviate the current situation of water resource shortage, and help thermal power plants achieve efficient recycling of industrial wastewater and even pure water output and utilization. However, membrane distillation technology itself still faces technical problems such as high energy consumption, short membrane life, and membrane flux attenuation. In the future, we should focus on the innovation of membrane materials, and develop membrane materials with longer service life, high anti-pollution ability, and lower cost. Establish new industry standards to verify the reliability, economy, and stability of long-term operation, and innovate thermal power plant business models to accelerate the rollout of membrane technology in this market.

References

Andrés-Mañas, J. A., Ruiz-Aguirre, A., Acién, F. and Zaragoza, G., (2018). Assessment of a pilot system for seawater desalination based on vacuum multi-effect membrane distillation with enhanced heat recovery. *Desalination,* vol. 443, pp. 110-121.

Chandra Bhoumick, M., Paul, S., Roy, S. and Mitra, S., (2023). Selective recovery of ethyl acetate by air-sparged membrane distillation using carbon nanotube-immobilized membranes and process optimization via a response surface approach. *Industrial & Engineering Chemistry Research,* vol. 62**,** no. 7, pp. 3307-3314.

Conidi, C., Macedonio, F., Ali, A., Cassano, A., Criscuoli, A., Argurio, P. and Drioli, E., (2018). Treatment of flue gas desulfurization wastewater by an integrated membrane-based process for approaching zero liquid discharge. *Membranes,* vol. 8**,** no. 4, p. 117.

Eryildiz, B., Yuksekdag, A., Korkut, S. and Koyuncu, İ., (2021). Performance evaluation of boron removal from wastewater containing high boron content according to operating parameters by air gap membrane distillation. *Environmental Technology & Innovation,* vol. 22, p. 101493.

Jia, F. and Wang, J., (2018). Treatment of flue gas desulfurization wastewater with near-zero liquid discharge by nanofiltration-membrane distillation process. *Separation Science and Technology,* vol. 53**,** no. 1, pp. 146-153.

Lee, S., Kim, Y. and Hong, S., (2018). Treatment of industrial wastewater produced by desulfurization process in a coal-fired power plant via FO-MD hybrid process. *Chemosphere,* vol. 210, pp. 44-51.

Li, F., (2020). Application and research progresses of technologies for zero-discharge of desulfurization wastewater from coal-fired power plants. *Technology of Water Treatment,* vol. 46**,** no. 12, pp. 17-24.

Liu, J. y., Jia, Y. j., Yang, F. l., Ren, L., Li, P., Wang, F. and Cheng, F. q., (2023). Research progress of zero liquid discharge pretreatment process for flue gas desulfurization wastewater from coal-fired power plants. *Inorganic Chemicals Industry,* vol. 55**,** no. 12, pp. 12-25.

Liu, Q. S., (2014). Application and comparison of'zero discharge'technology for desulfurization waste water. *Thermal Power Generation,* vol. 43**,** no. 12, pp. 114-117.

Ministry of Water Resources of the People's Republic of China, (2022). *National Water Resources Bulletin,* Beijing: Ministry of Water Resources of the People's Republic of China.

Ministry of Water Resources of the People's Republic of China, (2024). *Water Resources Bulletin 2024,* Beijing: Ministry of Water Resources of the People's Republic of China.

National Bureau of Statistics, (2023). *China Statistical Yearbook 2023,* Beijing: China Statistics Press.

Sharan, P., Yoon, T. J., Thakkar, H., Currier, R. P., Singh, R. and Findikoglu, A. T., (2022). Optimal design of multi-stage vacuum membrane distillation and integration with supercritical water desalination for improved zero liquid discharge desalination. *Journal of Cleaner Production,* vol. 361, p. 132189.

Sun, Z. Y. and Shen, M. Z., (2018). Case study on zero discharge engineering of desulphurization wastewater in coal-fired power plants. *Industrial Water Treatment,* vol. 38**,** no. 10, pp. 102-105.

Wan, Y. G., Xu, F., Tian, X. F., Zhao, L. X. and Wang, X., (2017). Guodian Hanchuan Power Generation Company Limited desulfurization waste water evaporative crystallization project process analysis. *Huadian Technology,* vol. 39**,** no. 10, pp. 74-76+80.

Wang, Z. F., (2021). *Research on the optimization of the zero discharge transformation scheme of wastewater in the whole thermal power plant:Take a power plant in Tianjin as an example.* Master's Thesis, Shandong Jianzhu University.

Xu, Z. Q., Zhao, Y. and Lu, M. N., (2020). Engineering case analysis of zero liquid discharge system of desulfurization wastewater in a power plant. *Electric Power Technology and Environmental Protection,* vol. 36**,** no. 2, pp. 6-12.

Yang, M., (2019). *Pilot test research on zero discharge of desulfurization wastewater from coal-fired power plants.* Master's Thesis, Beijing University of Chemical Technology.

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Conflicts of Interest

The authors declare no conflict of interest.

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