

## Comparative Analysis of Seawater- and Calcium-Based Desulphurization of Aluminium Cell Fumes

Zongbing Liu<sup>1</sup>, Jing Liu<sup>2</sup>, Yungang Ban<sup>3</sup>, Qingchen Yang<sup>4</sup> and Longyuan Chen<sup>5</sup>

1. Process Engineer

2. Director of Electrolysis Process Department

3. Vice President

4. President

5. Process Engineer

Northeastern University Engineering & Research Institute (NEUI), Shenyang, China

Corresponding author: 2504646161@qq.com

<https://doi.org/10.71659/icsoba2025-al059>

### Abstract

In recent years, influenced by factors such as raw material, fuel, and transportation costs, the deployment of aluminium smelter projects at coastal ports has become a prevailing trend in the industry. This paper takes a large-scale newly built aluminium smelter project abroad as a case study to conduct an in-depth comparative analysis of seawater desulphurization and calcium-based desulphurization (limestone-gypsum process) for pot fume. The research results indicate that both technologies are technically feasible in meeting ultra-low emission requirements. However, seawater desulphurization offers a simpler process, reduced equipment maintenance workload, and operating costs that are 12 % lower than those of calcium-based desulphurization. Given the specific project conditions (coastal location, suitable seawater alkalinity, favourable dispersion conditions, and moderate distance for seawater intake and discharge), the seawater desulphurization system has clear advantages. It avoids issues related to solid by-products and complex wastewater treatment, offers better environmental compatibility, and not only effectively achieves ultra-low flue gas emissions but also aligns with the aluminium industry's goals for clean production and sustainable development.

**Keywords:** Aluminium electrolysis cell fume, Seawater desulphurization, Calcium-based desulphurization.

### 1. Introduction

The fume produced during aluminium electrolysis (hereinafter referred to as "pot fume") mainly contains dust, fluorides, and the gaseous pollutant sulphur dioxide (SO<sub>2</sub>). Among these, SO<sub>2</sub>, due to its large total emissions, has become a key target of environmental control. The SO<sub>2</sub> in pot fume primarily originates from sulphur content in prebaked anodes [1]. Under the high-temperature environment (~960 °C) of electrolysis cells, the sulphur in anode carbon blocks is oxidized to generate SO<sub>2</sub>. It is noteworthy that in recent years, influenced by raw material availability and cost, the use of medium- to high-sulphur petroleum coke (typically containing 2–3 % sulphur, sometimes as high as 5 %) in prebaked anode production has increased [2], directly leading to a significant rise in SO<sub>2</sub> concentrations in pot fume, thus placing higher demands on end-treatment technologies.

Wet desulphurization technology, due to its high removal efficiency and proven reliability, dominates the field of pot fume treatment in China (with an application rate of approximately 74 %) [3]. Major wet desulphurization technologies include the calcium-based process (limestone-gypsum method), seawater process, and ammonia process. The calcium-based method is mature and widely used [4], but its system is complex and generates by-product gypsum and wastewater requiring treatment; in contrast, the seawater method makes full use of the natural

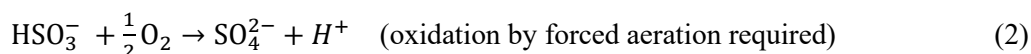
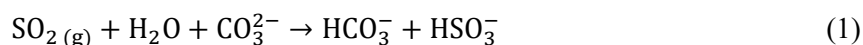
alkalinity (mainly containing  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$  etc.) and buffering capacity of seawater as the absorbent [5]. However, its application is significantly limited by geographic conditions, making it suitable only for coastal aluminium plants with convenient seawater intake and discharge.

With the implementation of domestic capacity “ceiling” policies for electrolytic aluminium, and increasing constraints on resources, energy, and the environment, Chinese aluminium smelters are accelerating capacity relocation to regions such as Southeast Asia and the Middle East that offer advantages in resources, energy, and port access. Against this backdrop, considering the logistics costs of raw material imports and product exports, as well as energy supply, building large-scale electrolytic aluminium bases in coastal port areas has become an irreversible industry trend. For such coastal projects, utilizing abundant seawater resources for pot fume desulphurization becomes a highly attractive option. However, the actual performance of seawater desulphurization is influenced by several key factors: seawater alkalinity (which directly affects absorption capacity), marine dispersion conditions (impacting compliance and ecological assessment), discharge water quality requirements (especially pollutant limits for heavy metals, Chemical Oxygen Demand or COD, etc.), and the engineering complexity and investment of the seawater intake and discharge system (transport distance, lift, anti-corrosion requirements), among others. Therefore, for newly constructed coastal aluminium smelter projects, this paper provides a scientific and objective comparative analysis of seawater and the mature calcium-based desulphurization technologies, evaluating their technical adaptability, economic viability, and environmental benefits, offering important practical guidance for project decision-making and green development in the industry.

## 2. Overview of Desulphurization Schemes

### 2.1 Seawater Desulphurization

Seawater desulphurization [6-10] utilizes the inherent alkalinity and strong acid-base buffering capacity of natural seawater to absorb  $\text{SO}_2$  from pot fume. The basic chemical reactions are as follows:



The absorption process causes a significant decrease in seawater pH (usually around 3). The treated acidic seawater requires forced aeration (injection of large amounts of air) to fully oxidize the unstable bisulphite ( $\text{HSO}_3^-$ ) to stable sulphate ( $\text{SO}_4^{2-}$ ). Subsequently, the oxidized seawater is usually mixed with a certain amount of fresh seawater for dilution, ensuring that the pH, temperature, and other water quality indicators (such as COD and heavy metal content) meet local strict discharge standards before being released back into the ocean. The inherent salts in seawater (mainly  $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{Mg}^{2+}$ , etc.) are the primary dissolved solids (TDS), and their concentration remains largely unchanged before and after treatment, despite the anion composition shifts (decrease in  $\text{HCO}_3^-/\text{CO}_3^{2-}$ , increase in  $\text{SO}_4^{2-}$ ).

The system mainly includes the flue gas system, absorption system, seawater recovery system, and the water intake and discharge system. The typical process flow is shown in Figure 1.

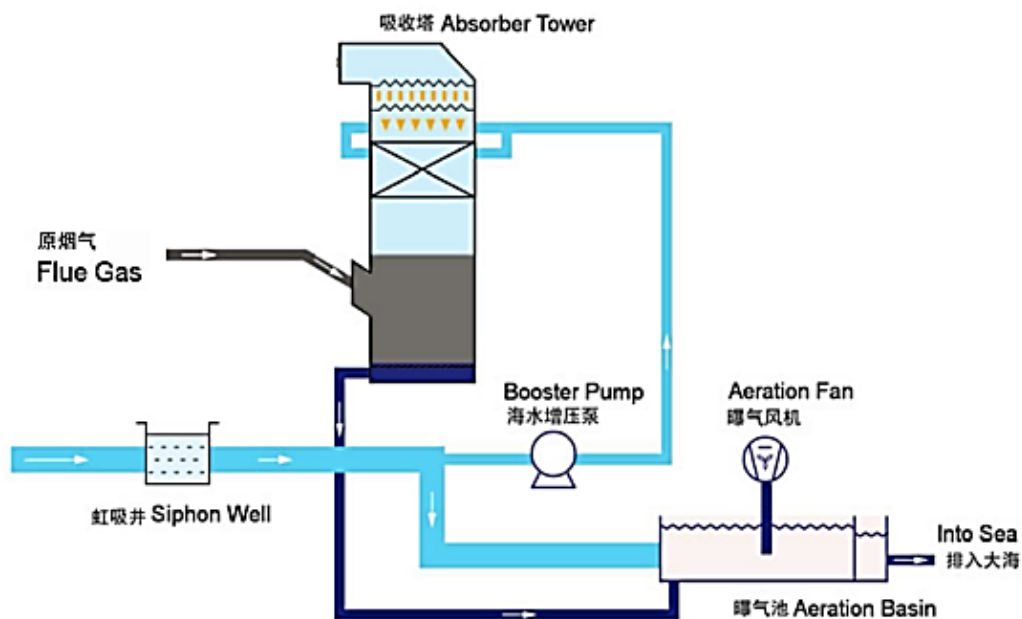
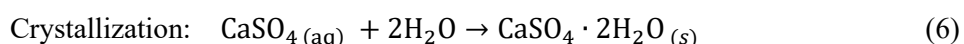
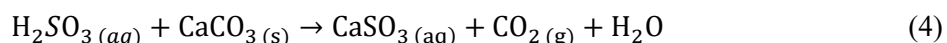
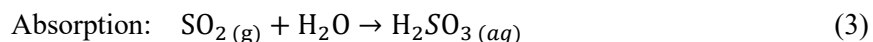


Figure 1. Seawater desulphurization process flow.

## 2.2 Calcium-Based Desulphurization

Calcium-based desulphurization (limestone-gypsum method) uses limestone slurry ( $\text{CaCO}_3$ ) as the absorbent [11]. The core chemical reactions are as follows:



In the absorption tower (typically a spray tower), the slurry is atomized into fine droplets by nozzles and comes into full contact with the upward-flowing flue gas, absorbing acidic gases such as  $\text{SO}_2$ ,  $\text{SO}_3$ , HF, and HCl. Oxidation air is blown into the slurry tank, where calcium sulphite ( $\text{CaSO}_3$ ) is forcibly oxidized to calcium sulphate ( $\text{CaSO}_4$ ) and crystallizes under supersaturated conditions to form dihydrate gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ). Limestone slurry is continuously replenished to maintain a constant pH value in the absorption slurry (usually controlled between 5.2 and 5.8).

The system mainly includes the flue gas system, absorbent preparation system, absorption system, by-product disposal system, emergency slurry system, process water system, and wastewater treatment system. The typical process flow is shown in Figure 2.

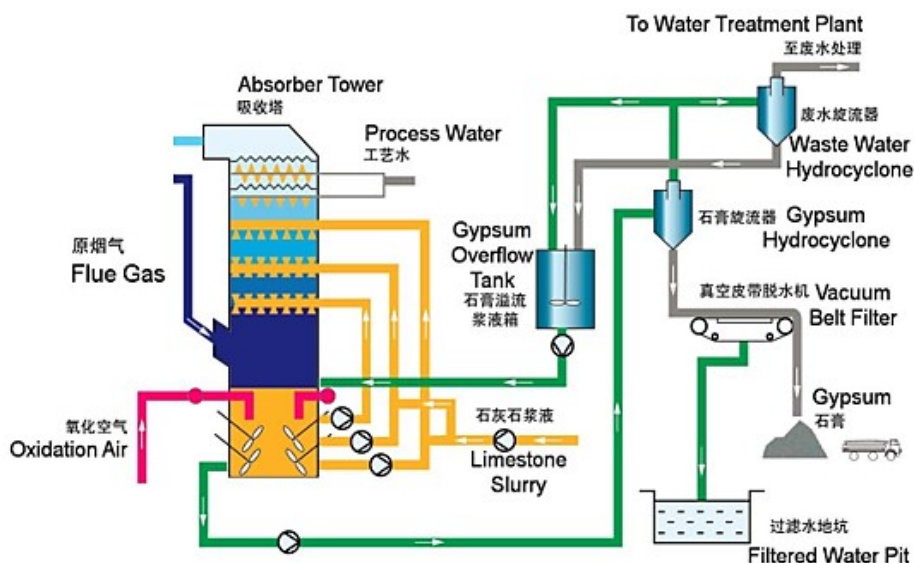


Figure 2. Calcium-based desulphurization process flow.

### 3. Comparison of Desulphurization Schemes

#### 3.1 Project Overview

This paper takes a foreign aluminium smelter project (hereinafter referred to as “the Project”) as an example, with a designed annual primary aluminium production capacity of 1 million tonnes, utilizing NEUI500 kA high-efficiency cell technology. The plant consists of two potlines, each one comprising 372 electrolysis cells. Each potline is divided into four sections, with one desulphurization system serving every two sections, totalling four desulphurization systems across the entire plant. Each desulphurization system is designed to treat 2 230 200 Nm<sup>3</sup>/h of fume (wet basis, actual O<sub>2</sub>) or 2 203 437 Nm<sup>3</sup>/h (dry basis, actual O<sub>2</sub>).

The sulphur content in the prebaked anodes used in this project is 2.1 %. The initial SO<sub>2</sub> concentration in the pot fume is approximately 260 mg/Nm<sup>3</sup> with dust ≤ 5 mg/Nm<sup>3</sup> and fluoride ≤ 1.5 mg/Nm<sup>3</sup>. Post-desulphurization emission targets are SO<sub>2</sub> ≤ 35 mg/Nm<sup>3</sup>, dust ≤ 5 mg/Nm<sup>3</sup>, and fluoride ≤ 0.5 mg/Nm<sup>3</sup>, meeting ultra-low emission requirements.

#### 3.2 Desulphurization Scheme

The project is located near a seaport, with abundant seawater resources and suitable alkalinity (2.2–2.5 mmol/L), favourable marine dispersion conditions, and relatively advantageous intake/discharge engineering conditions (plant elevation at approximately 9 m, seawater intake/discharge distance around 1.5 km). Therefore, both seawater desulphurization and calcium-based desulphurization schemes are viable for comparative evaluation.

### 3.2.1 Comparison of Main Technical Characteristics

Respective characteristics are summarized in the following Table1.

**Table 1. Comparison of main technical characteristics.**

Item	Unit	Seawater Desulphurization	Calcium-Based Desulphurization	Remarks
Technology Maturity	/	Mature	Very mature	
Process Complexity	/	Relatively simple	Complex	
Desulphurization By-products	/	None	Yes (Gypsum)	
Treated Pot Fume Volume (Wet basis, actual O <sub>2</sub> )	Nm <sup>3</sup> /h	2 230 200	2 230 200	Single tower
Treated Pot Fume Volume (Dry basis, actual O <sub>2</sub> )	Nm <sup>3</sup> /h	2 203 437	2 203 437	Single tower
Inlet SO <sub>2</sub> Concentration (Dry basis, actual O <sub>2</sub> )	mg/Nm <sup>3</sup>	≤ 260	≤ 260	
Outlet SO <sub>2</sub> Concentration (Dry basis, actual O <sub>2</sub> )	mg/Nm <sup>3</sup>	≤ 35	≤ 35	
Absorbent Type	/	Seawater	Limestone	
Absorption Tower Type	/	Packed Tower	Spray Tower	
Fan Configuration	/	Combined ID/Booster	Combined ID/Booster	
Absorbent Preparation/Process	/	Fresh seawater / Once-through	Powder slurry / Circulating	
System Resistance	Pa	≤ 1300	≤ 1000	
Key Constraints	/	Seawater alkalinity, water quality, intake/discharge conditions, environmental regulations	Limestone supply and quality, gypsum disposal, wastewater treatment	Dependence on project site and external conditions varies
Secondary Pollution/Waste		No solid waste, treated water discharged to sea	Gypsum solid waste generated and wastewater requires treatment	

### 3.2.2 Comparison of Major Equipment Configurations

The next Table 2 summarizes the respective equipment configurations.

**Table 2. Comparison of major desulphurization equipment configurations.**

Item	Seawater Desulphurization	Calcium-Based Desulphurization
Flue Gas System	Flue, damper gate	Flue, damper gate
Absorbent Preparation System	Seawater lifting pump, seawater booster pump station	Limestone powder silo, silo top dust collector, metering screw conveyor, limestone slurry feed pump
Absorption System	Absorption tower (packed tower), flat-plate/chevron demister, seawater distributor/spray layer	Absorption tower (spray tower), chevron demister (multi-stage), spray layers (multi-layer), slurry circulating pumps (multiple, high-power), oxidation fan, agitator
By-product Handling System	Aeration fan, aeration basin	Gypsum cyclone, vacuum belt filter, dewatering workshop, gypsum storage
Emergency Slurry System	None	Emergency slurry tank, emergency slurry pump
Process Water System	Closed-circuit cooling water system (mainly for equipment cooling)	Process water tank, multiple process water pumps, demister wash pumps, equipment seal cooling water system
Wastewater Treatment System	None	Wastewater treatment unit and discharge system (neutralization, flocculation, sedimentation, clarification, sludge dewatering, etc.)
Key Differences	Fewer total equipment, no solid waste/wastewater treatment equipment, core component is aeration system	Larger and more complex equipment setup, core components include slurry circulation pumps, oxidation fan, and gypsum dewatering system; wastewater treatment is mandatory

### 3.2.3 Material and Power Consumption

#### 1) Seawater Desulphurization

The seawater desulphurization system features a simple process design and produces no by-products; treated seawater can be directly discharged into the sea once standards are met, with no need for dedicated wastewater treatment. Based on the sulphur content in the project's pot fume and under ultra-low emission conditions, seawater consumption is approximately 400 m<sup>3</sup>/t Al, equipment cooling water consumption is 0.07 m<sup>3</sup>/t Al, and desulphurization system power consumption is around 50 kWh/t Al under full-load pot fume conditions (including the share of induced draft fan power consumption assigned to the desulphurization system). Detailed parameters are shown in Table 3.

**Table 3. Seawater desulphurization material and power consumption.**

Item	Unit	Value
Seawater Consumption	m <sup>3</sup> /t Al	400
Cooling Water Usage	m <sup>3</sup> /t Al	0.07
Power Consumption	kWh/t Al	50

#### 2) Calcium-Based Desulphurization

The calcium-based desulphurization system offers high efficiency but generates gypsum as a by-product and produces desulphurization wastewater during the process. Based on the sulphur

content in the project's pot fume and under ultra-low emission conditions, the absorbent ( $\text{CaCO}_3$ ) consumption is approximately 22 kg/t Al. The desulphurization by-product (gypsum) output is 39 kg/t Al, and under full-load pot fume conditions, the desulphurization system consumes approximately 65 kWh/t Al. Process water consumption is around 2 m<sup>3</sup>/t Al, and desulphurization wastewater discharge is 0.03 m<sup>3</sup>/t Al. Detailed parameters are shown in Table 4.

**Table 4. Calcium-based desulphurization material and power consumption.**

Item	Unit	Value	Remarks
Desulphurizing Agent	kg/t Al	22	Purity not less than 90 %
Desulphurization By-product (Gypsum)	kg/t Al	39	
Desulphurization Wastewater Discharge	m <sup>3</sup> /t Al	0.03	

### 3.2.4 Cost Estimation

#### 1) Construction Costs

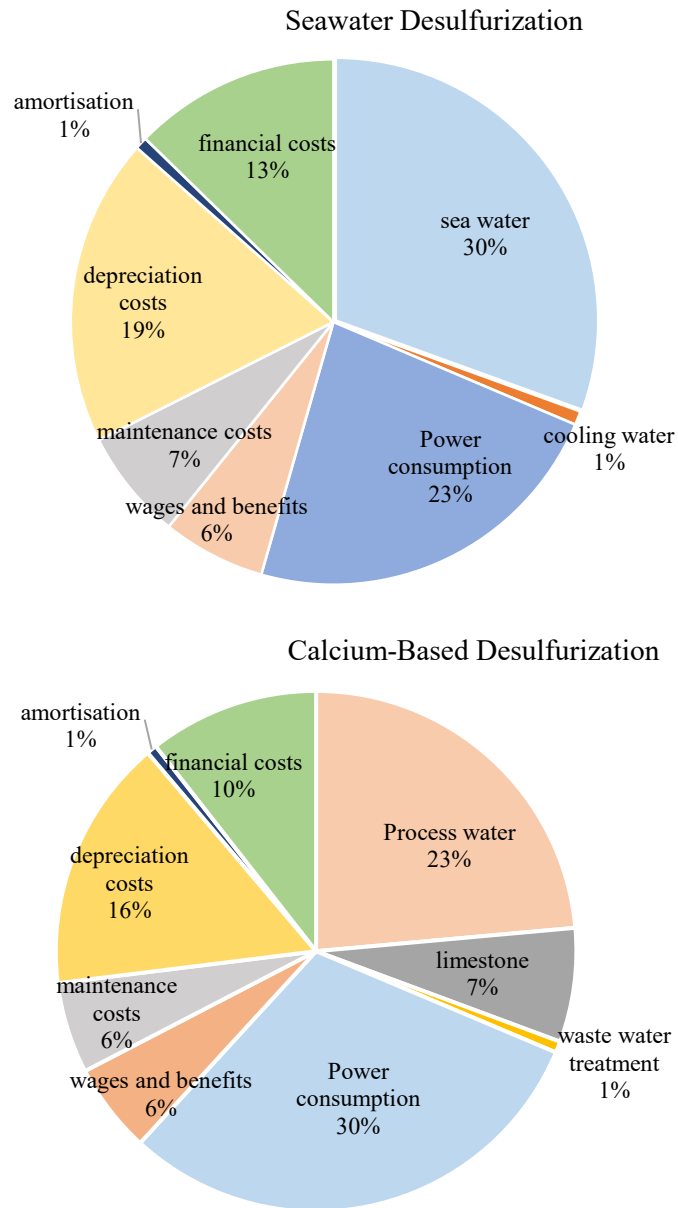
According to the project feasibility study, the estimated investment for four seawater desulphurization systems is 212 million RMB (29.3 MUSD approx., excluding intake and discharge water systems, induced draft fans, and flues before the absorption tower). The estimated investment for four calcium-based desulphurization systems is 201 million RMB (27.8 MUSD approx., excluding induced draft fans and flues before the absorption tower). Therefore, the equivalent construction investment cost for seawater desulphurization is 215 RMB/t Al, and for calcium-based desulphurization, it is 201 RMB/t Al (approximately 29.7 and 27.8 USD/t Al respectively). Under specific project conditions (intake and discharge distance of 1.5 km and site elevation of 9 m), the construction investment intensity for both desulphurization options is very similar and essentially at the same level.

#### 2) Operating Costs

Under conditions where the  $\text{SO}_2$  concentration at the inlet of the desulphurization system is approximately 260 mg/Nm<sup>3</sup>, and the emission concentration is  $\leq 35$  mg/Nm<sup>3</sup>, the unit costs for materials and power consumption are as follows: Desulphurizing agent limestone ( $\text{CaCO}_3$ ) at 230 RMB/t (31.8 USD/t limestone approx.); Electricity price at 0.35 RMB/kWh (48 USD/MWh approx.); Process water (desalinated seawater/industrial water) at 8 RMB/m<sup>3</sup> (1.1 USD/m<sup>3</sup> approx.); Wastewater treatment costs at 5 RMB/m<sup>3</sup> (0.69 USD/m<sup>3</sup> approx.); Seawater comprehensive unit price (including intake, discharge energy consumption, maintenance, etc.) at 0.05 RMB/m<sup>3</sup> (6.9 mUSD/m<sup>3</sup> approx.); Per capita salary and welfare at 130 000 RMB per year per person (18 kUSD/ft.e.year approx.); Maintenance costs at 3 % of the total equipment cost; Building and construction depreciation period at 20 years, mechanical equipment depreciation period at 15 years, and a 5 % net residual value rate for buildings, structures, and mechanical equipment.

Under full-load pot fume conditions and ultra-low emission requirements, the operating cost for the seawater desulphurization system is 65.5 RMB/t Al (9.1 USD/t Al approx.), where seawater transportation costs account for 30 % of the total cost, and electricity costs account for 23 % of the total operating cost. The operating cost for the calcium-based desulphurization system is 74.7 RMB/t Al (10.3 USD/t Al approx.), with electricity costs accounting for 30 % of the total operating cost, and process water consumption accounting for approximately 23 % of the total operating cost. For this project, the operating costs of the seawater desulphurization system are better than those of the calcium-based desulphurization system, reducing the operating cost by 9.2 RMB/t Al (1.3 USD/t Al approx.), or a 12 % reduction.

A breakdown of the major operating cost proportions is shown in Figure 3.



**Figure 3. Comparison of operating cost composition ratios (upper: seawater desulfurization, lower: calcium-based desulfurization).**

### 3.3 Comprehensive Analysis

This project is located along the coast, with abundant seawater resources, favourable water quality (alkalinity 2.2–2.5 mmol/L), and good dispersion conditions. The intake/discharge distance is moderate, and the site elevation is relatively low, all of which provide favourable conditions for the application of seawater desulfurization. Considering the characteristics of large pot fume volume and relatively low inlet SO<sub>2</sub> concentration in this smelter project, and based on a techno-economic comparison, the analysis results are as follows:

(1) Both desulphurization technologies can reliably meet ultra-low emission requirements. The seawater desulphurization process is simple and involves fewer pieces of equipment, resulting in significantly lower maintenance workload compared to the calcium-based desulphurization system (eliminating numerous rotating parts and clog-prone/wear-prone/scaling-prone components such as slurry circulation pumps, agitators, dewatering equipment, and wastewater treatment units).

(2) The core advantage of seawater desulphurization lies in its generation of no solid waste and no complex or difficult-to-treat process wastewater. Treated seawater that meets standards can be directly discharged into the sea. Its environmental footprint primarily consists of converting sulphur into sulphate, which naturally exists in seawater, while slightly increasing the local  $\text{SO}_4^{2-}$  concentration and causing a minor temperature rise. Potential long-term impacts on marine ecosystems require strict environmental impact assessments and continuous monitoring and management.

(3) Calcium-based desulphurization systems inevitably produce gypsum as a by-product (with impurities affecting quality and marketability) and require treatment of desulphurization wastewater (containing high salinity, fluorides, chlorides, heavy metals, etc.), which is both technically challenging and costly.

(4) For coastal projects with favourable seawater conditions, the operating cost of seawater desulphurization is lower (by 12 %). Its system is simpler and more streamlined, with fewer potential failure points and relatively lower risk of unplanned shutdowns.

(5) The applicability of seawater desulphurization is highly dependent on specific site conditions: seawater quality (alkalinity, temperature, turbidity, background pollutants), feasibility of intake/discharge engineering (distance, elevation, geology, marine use permits), environmental capacity (discharge standards, mixing zone requirements, ecological sensitivity), and local regulations. Calcium-based desulphurization has broader adaptability but faces challenges in resource consumption and waste generation.

#### **4. Conclusions**

Based on the study in this paper, the following conclusions are drawn:

1) Under the specific conditions of this project, the construction investment intensity per tonne of aluminium for seawater and calcium-based desulphurization systems is essentially equivalent. However, the direct operating cost of seawater desulphurization is 12 % lower than that of calcium-based desulphurization. The main cost of the seawater desulphurization system lies in electricity for seawater transport, while the cost of the calcium-based system is mainly distributed among electricity consumption (slurry circulation pumps), process water, and limestone.

2) Seawater desulphurization technology is mature and reliable, with simplified processes and significantly fewer pieces of equipment and maintenance workload compared to the calcium-based system. The desulphurization absorbent is natural seawater, requiring no chemical additives. After adequate aeration, oxidation, and proper dilution, the treated seawater can be discharged directly into the sea once standards are met, effectively addressing the wastewater treatment challenge of wet desulphurization and offering superior environmental compatibility.

3) Given the project's excellent coastal conditions, the significant advantages of seawater desulphurization in terms of operating costs and environmental benefits, and its technical capability to meet ultra-low emissions, the seawater desulphurization solution is recommended for this project. The implementation of this project will serve as a significant demonstration for clean production in coastal aluminium smelter projects.

## 5. References

1. Zhuxian Qiu, *Prebaked Cell Aluminium Smelting* (3rd Edition) [M], Metallurgical Industry Press, 2005 (in Chinese).
2. Yongjian Yuan, Lili Huang. Brief Analysis of Pot fume Desulphurization Technologies for Electrolysis Cells [J], *Light Metals*, 2019(7): 33–36, 45 (in Chinese).
3. Shanshu Lao and Zhijie Zhao, Selection of Desulphurization Technology for pot fume [J], *Light Metals*, 2023(7): 54–57 (in Chinese).
4. Zongbing Liu, Comparative Study on Desulphurization Technology Schemes for Pot Fume [J], *China Science & Technology Overview*, 2024(6): 94–96 (in Chinese).
5. Hongjun Lv and Xunhai Wu, Application and Development of Seawater Desulphurization Technology [J], *Energy Conservation and Environmental Protection*, 2005(4) (in Chinese).
6. Jun Xue et al., Research and Application of Seawater Pot fume Desulphurization Technology [J], *Electric Power Science and Environmental Protection*, 2010, 26(1): 36–38 (in Chinese).
7. Dong Yang et al., *Seawater Pot fume Desulphurization Technology and Demonstration Report for Large-Scale Coal-Fired Power Plants* [R], 2011 (in Chinese).
8. Lifeng Li and Shushen Zhang, Comparative Study on Seawater and Limestone/Lime-Gypsum Desulphurization Schemes in Thermal Power Plants [J], *Chemical Equipment Technology*, 2006(4): 60–62 (in Chinese).
9. Yingying Zhao et al., Research Progress on Integration of Seawater Decalcification and Pot fume Carbonation Desulphurization [J], *Chemical Industry and Engineering Progress*, 2020, 39(11): 4315–4329 (in Chinese).
10. Hui Lv and Fengchun Lan, Application Research on Seawater Flue Gas Desulphurization Process in Domestic Thermal Power Plants [J], *Jilin Electric Power*, 2007, 35(4): 23–26, 30 (in Chinese).
11. Tianbao Lv, *Industrial Desulphurization and Comprehensive Utilization Technology* [M], *National Defense Industry Press*, 2011 (in Chinese).