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Acid Gas Emission Reduction Efficiency of Sodium Bicarbonate Compared to Slaked Lime in Waste Incineration Facilities

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Abstract

This study was conducted with the purpose of empirically comparing and analyzing the reaction efficiency and cost-effectiveness of sodium bicarbonate ($NaHCO_3$) and highly reactive hydrated lime ($Ca(OH)_2$), which are used as acid gas neutralizing agents in the Dry Reactor (DR) process of waste incineration facilities. The subjects of the study were selected from four incineration facilities at industrial sites with similar incineration capacities and air pollution control facility configurations. Based on actual operating data, the amount of neutralizing agents used, the amount of fly ash generated, and the amount of agents used in downstream wet scrubbing facilities were comprehensively compared.

As a result of the study, an analysis was conducted by converting chemical costs, fly ash treatment costs, and wet scrubbing facility chemical costs based on the same incineration volume. The study found that the application of sodium bicarbonate resulted in a reduction of total operating costs ranging from a minimum of 9.1% to a maximum of 27.8% compared to slaked lime. This is attributed to the reduced load on downstream pollution control facilities and lower fly ash treatment costs due to the high reactivity of sodium bicarbonate. Therefore, it was confirmed that when selecting neutralization chemicals for the acid gas treatment process in waste incineration facilities, it is necessary to evaluate treatment efficiency by comprehensively considering not only the unit price of the chemical but also reaction efficiency, fly ash generation characteristics, downstream facility operating costs, and environmental impact.

Keywords : Waste incineration, Acid gas, Sodium bicarbonate, Hydrated lime, Treatment efficiency, Economic analysis.

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1. Introduction

1.1. Research Background

Acid gases and hazardous air pollutants generated from waste incineration facilities are recognized as major pollutants that have long-term effects on human health and the environment, and accordingly, the international community is demanding emission reductions through various environmental agreements and regulations. In particular, high-temperature heat treatment processes such as incineration can unintentionally generate hydrogen chloride (HCl), sulfur oxides (SO_2), and nitrogen oxides

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(NOx), as well as persistent organic pollutants such as dioxins and furans, thus emphasizing the need for international management.

In Europe, serious environmental problems arose during the industrialization process, as acidic gases such as sulfur oxides (SO_2), nitrogen oxides (NOx), and hydrogen chloride (HCl), emitted from fossil fuel combustion and waste incineration facilities, traveled long distances through the atmosphere and combined with precipitation to form acid rain, causing the acidification of soil, forests, lakes, and rivers. Since this problem had a widespread impact transcending national borders, the establishment of international cooperation and regulatory frameworks became necessary.

Against this backdrop, the Convention on Long-Range Transboundary Air Pollution (CLRTAP) was concluded in 1979 under the leadership of the United Nations Economic Commission for Europe (UNECE). This convention is regarded as the first regional environmental agreement aimed at curbing the long-distance transport of air pollution and protecting the environment and human health, centered on Europe and North America, and set the resolution of the acid rain problem as a major objective. The convention defined air pollution as “pollution originating within the jurisdiction of one country and affecting the environment of another country” and promoted joint responses among member states and the establishment of emission reduction policies.

In particular, acid gas emissions are a major subject of environmental regulation for waste incineration facilities; accordingly, evaluating the reaction efficiency and economic feasibility of neutralizing agents applied in dry reaction towers is recognized as a critical technical challenge in terms of responding to international environmental regulations. While waste incineration facilities are key treatment systems capable of simultaneously achieving waste reduction and energy recovery, they emit large quantities of acid gases, such as hydrogen chloride (HCl) and sulfur oxides (SOx), during the combustion process. These acid gases are a major cause of air pollution and incur environmental and social costs when emission standards are exceeded.

Domestic waste incineration facilities generally utilize a complex air pollution control system consisting of a Dry Reactor (DR), a Bag Filter, and a Wet Scrubber. Among these, the type of neutralizing agent injected into the DR and the operating method have a significant impact not only on the overall acid gas removal efficiency but also on the amount of fly ash generated, the load on downstream pollution control facilities, the amount of wastewater generated, and the total operating costs.

1.2. Necessity of Research

Highly reactive hydrated lime ($Ca(OH)_2$) has traditionally been widely used in dry reaction towers (DR) of domestic incineration facilities, but recently, the high reactivity and stable removal efficiency of sodium bicarbonate ($NaHCO_3$) have been attracting attention. There are a considerable number of studies on the efficiency of hydrated lime and baking soda as neutralizing agents used as acid gas neutralizers in waste incineration DR facilities, and most have shown that baking soda is more effective than hydrated lime in neutralizing acid gases. Recently, as the domestic distribution price of baking soda has decreased, many incineration facility operators who had previously refrained from using baking soda due to high costs are now reconsidering its use.

Most existing studies have focused on the acid gas removal efficiency of baking soda and quicklime in DR, and comparative economic studies that comprehensively consider the unit cost and input amount of neutralizing chemicals, fly ash treatment costs, and chemical costs used in downstream wet scrubbers are limited. In particular, empirical analysis based on incineration plant operation data is very lacking.

1.3. Research Purpose

The purpose of this study is as follows.

First, the chemical reaction characteristics of sodium bicarbonate and highly reactive slaked lime used in waste incineration DR facilities are compared. Depending on how each chemical specifically reacts in the DR, measures or alternatives for optimal efficiency can be established.

Second, based on the same acid gas removal effect, the amount of chemical input, the amount of fly ash generated, and the amount of chemicals used for acid gas neutralization in the downstream wet scrubber are quantitatively evaluated. This is because simply comparing the treatment efficiency of each chemical used in the DR makes it difficult to compare the costs required to treat acid gases generated across the entire waste incineration facility.

Third, economic feasibility is compared and analyzed from the perspective of total operating costs based on actual incineration facility operation data. Research on acid gas treatment efficiency will ultimately be valuable only when applied to actual industrial sites. It is important to verify how reaction efficiency manifests in actual industrial settings for each plant operating an incineration facility.

1.4. Research Subjects and Methods

This study targeted the incineration facilities of four factories operating waste incineration facilities. Since each facility has a similar incineration capacity and pollution control facility configuration, they were selected as research subjects to compare and analyze actual operating costs according to the type of neutralizing agent. A method was applied to compare and examine differences in the capacity and actual incineration volume of each facility, the usage and unit price of chemicals, and the concentration of pollutants emitted from the chimney.

2. Acid Gas Treatment Process

2.1. Acid Gas Generation Characteristics

Waste incineration facilities are widely utilized as treatment facilities that simultaneously achieve volume reduction and stabilization by burning municipal and industrial waste at high temperatures. However, during the combustion process, various inorganic and organic components undergo thermal decomposition and oxidation reactions, generating acidic gases such as hydrogen chloride (HCl) and sulfur oxides (SOx). Since these acidic gases act as major causes of air pollution and equipment corrosion, they are managed as pollutants that must be reduced during the operation of incineration facilities.

During waste incineration, hydrogen chloride is primarily generated by the thermal decomposition and oxidation reactions of chlorine components contained within the waste. Municipal solid waste contains a mixture of chlorine-based plastics such as polyvinyl chloride (PVC), food residues containing sodium chloride, and various chlorine-containing chemicals; these substances decompose in the high-temperature environment of the incinerator, converting into chlorine radicals or hydrogen chloride. Additionally, inorganic chlorine compounds within the waste can also form hydrogen chloride during combustion in the presence of acid and moisture, and the amount produced can vary significantly depending on the incinerator temperature, oxygen concentration, and gas residence time. Furthermore, inorganic chlorine compounds in waste can also form hydrogen chloride during combustion in the presence of acid and moisture, and the amount produced can vary significantly depending on the incinerator temperature, oxygen concentration, and gas residence time. Consequently, the generation of hydrogen chloride is understood as the result of a complex thermochemical reaction influenced simultaneously by the chlorine content in the waste composition and combustion conditions.

Meanwhile, sulfur oxides are air pollutants generated when sulfur components contained in waste are oxidized; sulfur compounds contained in rubber, synthetic fibers, protein-based organic matter, sludge, and some industrial waste act as the main sources of generation. In the high-temperature oxidizing atmosphere inside an incinerator, sulfur is converted into sulfur dioxide (SO_2) through combustion reactions, and subsequently, some of it can be oxidized to sulfur trioxide (SO_3) in the flue gas by oxygen or catalytic conditions. The generated SO_3 can react with moisture to form sulfuric acid mist, which is a factor that contributes to equipment corrosion and the formation of fine dust.

Table 1: Waste composition analysis [Unit : %]

Types of incinerated waste		Cl	S
Waste synthetic resin from industrial sites		1.2	0.1
Volume-based waste disposal	Household sector	0.5	0.14
	Non-household sector	0.46	0.13

According to the 6th National Waste Statistics Survey in 2022, as shown in Table 1, a certain amount of chlorine and sulfur components exist in industrial waste and volume-based household waste, and when these chlorine and sulfur components are incinerated in waste incineration facilities, they are emitted as acidic gases such as hydrogen chloride and sulfur oxides.

As such, hydrogen chloride and sulfur oxides generated during the waste incineration process are explained as thermodynamic and reaction-kinetic phenomena that are complexly influenced by operating conditions such as the chemical composition of the waste, combustion temperature, oxygen supply status, and flue gas residence time. In particular, since acidic gases generated in the high-temperature combustion zone can undergo additional reactions and transformations during downstream cooling and flue gas treatment processes, it is essential to establish neutralization and removal strategies that consider these generation mechanisms when designing the flue gas treatment process of an incineration facility.

2.2. Acid Gas Treatment Process Configuration

The flue gas treatment process of domestic municipal solid waste incineration facilities is generally most often composed of a semi-dry reaction tower (SDR), a bag filter, and a selective catalytic reduction (SCR) system, and in some facilities, a combined treatment process is applied in which a wet scrubber is additionally installed at the downstream end.

Table 2: Configuration of pollution control facilities by incineration facility

City	Facility Name	Air Pollution Control Devices Configuration	Remarks
Seoul	Gangnam Resource Recovery Facility	Scrubber –SDR – B.F(Bag Filter) – SCR	Multi-stage APCD system
Seoul	Yangcheon Resource Recovery Facility	Scrubber –SDR – B.F – SCR	Typical metropolitan configuration
Seoul	Mapo Resource Recovery Facility	SDR – B.F – E.P(Electrostatic Precipitator) – SCR – Scrubber	Advanced multi-pollutant control
Seoul	Nowon Resource Recovery Facility	SDR – B.F – E.P – SCR – Scrubber	Large-scale urban incinerator
Gunpo City	Gunpo Environmental Management Center	SDR – B.F – SCR	Standard dry treatment configuration
Gimhae City	Gimhae MSW Incineration Plant	SDR – B.F – SCR	Typical modern configuration
Uijeongbu City	Uijeongbu Resource Recovery Facility	SDR – B.F – SCR	Standard acid gas control
Miryang City	Miryang MSW Incineration Facility	SNCR – SDR – Activated Carbon & Hydrated Lime Injection – B.F r – SCR	Enhanced air pollution control
Inje County	Inje MSW Incineration Facility	SDR – B.F – SCR	Small-scale municipal facility
Gwacheon City	Gwacheon Environmental Treatment Center	SDR – B.F – Gas Heater – SCR – Stack	Includes gas reheating system

Table 2 shows the configuration of major municipal solid waste treatment facilities in the capital area of Korea. The basic air pollution control facilities of municipal solid waste incineration facilities in Korea generally consist of a combination of semi-dry reaction towers (SDR), bag filters, and selective catalytic reduction (SCR) systems, while some large cities have installed and operate multi-stage combined pollution control facilities including scrubbing towers and electrostatic precipitators.

2.3. Unit Price and Supply Characteristics of Neutralizing Agents

Representative DR neutralizing agents distributed domestically are baking soda and highly reactive slaked lime, and the characteristics of these agents are as shown in Table 3.

Table 3: Characteristics of DR Acid Gas Neutralizing Agents

Division	Sodium bicarbonate	Slaked lime
Chemical formula and content	$NaHCO_3$, Approximately 94%	$Ca(OH)_2$, Approximately 84%
Particle size or Mesh	325 Mesh, 44 μm	800 Mesh, 15 μm
Distribution Unit Price (2026.01)	320 won/kg	320 won/kg
Domestic Production /Importer	Domestic: No manufacturers, 100% imported Importers: Unico Fine Chemical, Chunghae Materials, CP Chem, OCI	Domestic: Taeyoung EME / Taekyung Industry Overseas: Imported products
Physical and chemical properties	①The salt produced after the neutralization reaction is soluble in water and has the property of being brittle. ②It readily absorbs moisture from the air. ③It adsorbs acidic gases and has high	①The salt produced after the neutralization reaction does not dissolve in water. ②The salt is hard, making it difficult to remove. ③The reaction proceeds via neutralization; compared to

	neutralization reaction efficiency at 100~190°C.	sodium bicarbonate, the reaction is slower and less efficient.
Handling characteristics	①It is necessary to block moisture inflow into storage tanks and transfer facilities (dehumidification device). ②Removal of generated salt is relatively easy.	①Lower hygroscopicity than sodium bicarbonate. ②The generated salt is hard, making it relatively difficult to remove compared to sodium bicarbonate.

In the case of sodium bicarbonate, there is no domestic production, and the entire supply relies on imports. The majority of imports come from China, and products with a mesh specification of approximately 250～285 are currently in circulation. Additionally, during the COVID-19 pandemic in 2022, the product was designated as non-exportable by China, causing domestic supply issues; however, as of January 2026, it is being supplied domestically without any distribution problems.

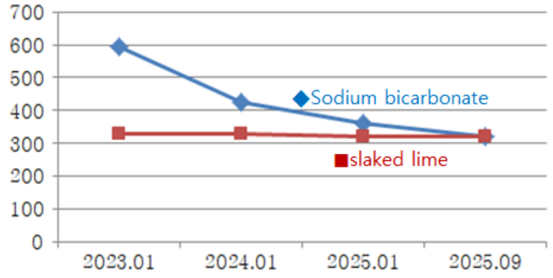

Figure 1. Domestic distribution unit prices of DR neutralizing agents

As shown in Fig. 1, the distribution unit price of sodium bicarbonate for DR (Drainage Reactor) in Korea decreased from 360 won/kg by August 2025 to 320 won/kg starting from the end of 2025, and continues to show a downward trend. This is due to the urgent demand for the product within China, the main export market.

As such, the high dependence on overseas sources, particularly China, for sodium bicarbonate means there is a high possibility that domestic import and distribution prices will fluctuate significantly depending on international trade and political environments.

On the other hand, in the case of highly reactive hydrated lime, the hydrated lime distributed domestically is mainly produced and distributed by two domestic companies. Due to the recent slump in the construction and steel industries, domestic consumption has decreased, and the reliance on demand from other industrial sectors is increasing, so a decline in domestic distribution unit prices can also be expected. Domestic production capacity for hydrated lime had been maintained at a constant level, but domestic competition is intensifying as Taekyung Industry, a major hydrated lime producer, has recently increased its production capacity.

2.4. Chemical Reaction of Acid Gases

It is known that the principle by which acidic gases are introduced into the DR and removed in the DR or downstream Bag Filter is based on adsorption and neutralization reactions. In "Evaluation of Acid Gas Removal Efficiency in Municipal Solid Waste Incineration Process Using Sodium Bicarbonate," it is explained that sodium bicarbonate undergoes thermal decomposition as shown in Equation (2) and Equation (3), and that neutralization reactions occur in a state where pores are developed. Additionally, quicklime can be explained by distinguishing between primary neutralization and complete neutralization reactions as shown in Equation (5) and Equation (6).

2.4.1. Sodium Bicarbonate

Sodium bicarbonate is converted into highly reactive sodium carbonate through a thermal decomposition process, and then reacts with acidic gases to form sodium chloride and sulfates.

Equation (1) is the reaction equation in which sodium bicarbonate reacts with hydrogen chloride.

$$NaHCO_3 + HCl \rightarrow NaCl + H_2O + CO_2 \quad (1)$$

When sodium bicarbonate reacts with sulfur oxides, it first undergoes thermal decomposition as in Equation (2), and then reacts as in Equation (3).

$$2NaHCO_3 \rightarrow Na_2CO_3 + CO_2 + H_2O \quad (2)$$

$$2NaHCO_3 + SO_2 + 1/2O_2 \rightarrow Na_2SO_4 + 2CO_2 + H_2O \quad (3)$$

If an oxidation reaction occurs simultaneously, it reacts as in Equation (4).

$$Na_2CO_3 + SO_2 \rightarrow Na_2SO_3 + CO_2 \quad (4)$$

Slaked lime reacts directly with acidic gases in the form of calcium hydroxide to produce calcium sulfite or calcium sulfate, and the reaction rate depends significantly on particle characteristics and residence time. Slaked lime neutralizes hydrogen chloride as shown in Equation (5).

$$Ca(OH)_2 + HCl \rightarrow Ca(OH)Cl + H_2O \quad (5)$$

Or, if a complete neutralization reaction occurs, the neutralization reaction is performed as in Equation (6).

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O \quad (6)$$

The neutralization reaction equation of slaked lime with sulfur oxides is as shown in Equation (7) and Equation (8).

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O \quad (7)$$

Or, under oxidizing conditions, it reacts as in Equation (8)

$$CaSO_3 + 1/2O_2 \rightarrow CaSO_4 \quad (8)$$

3. Acid Gas Treatment Efficiency

3.1. Facilities and Equipment under Study

As shown in Table 4, the waste incineration facilities under study were the incineration facilities at Company T's Plants A, B, C, and D.

Table 4: Pollution Control Facilities by Study Subject

Factory	Incineration capacity	Configuration of prevention facilities
Plant A	5.5 t/h	Cyclone - DR - Bag Filter - SCR - Wet Scrubber - Stack
Plant B	5.5 t/h	Cyclone - DR - Bag Filter - SCR - Wet Scrubber - Stack
Plant C	8.0 t/h	Cyclone - DR - Bag Filter - Wet Scrubber - Stack
Plant D	4.0 t/h	Cyclone - DR - Bag Filter - SCR - Wet Scrubber - Stack

All four plants utilize a DR (Dry Reactor) system that injects a neutralizing agent into the duct without configuring a separate reaction facility. For each site, the neutralizing agent was injected into the DR duct, adopting a method where acidic gases are controlled through adsorption and neutralization reactions in the bag filter. Each waste incineration facility under study belongs to the same industry and company. However, the neutralizing agents used for acidic gas treatment in the DR differ. Plants A, B, and C use baking soda, while Plant D uses quicklime. Since the capacities of the waste incineration facilities at each plant vary slightly, errors due to incineration capacity were corrected in the experimental results. Plants A, B, and D are equipped with Selective Catalytic Reduction (SCR) systems, but Plant C is not. However, since the SCR is not a facility directly involved in the neutralization of acid gases, its influence is to be ignored when interpreting the experimental results in this study.

3.2. Relationship with Downstream Prevention Facilities

Among the pollution control facilities of the waste disposal facilities at the four plants under study, the Wet Scrubber is the pollution control facility directly related to the removal of acidic gases. Although Bag Filters can treat acidic gases until neutralizing agents accumulate in the filter and are depleted, and thus affect efficiency, the influence of Bag Filters is to be ignored in this study. In this case, the amount of neutralizing agents used in the downstream Wet Scrubber varies depending on the amount of neutralizing agents injected from the DR. If the amount of neutralizing agents used in the DR increases, the amount of neutralizing agents used in the Wet Scrubber decreases. Conversely, if the amount of neutralizing agents used in the DR decreases, the amount of neutralizing agents used in the Wet Scrubber increases.

The neutralizing agent used in the Wet Scrubbers of the four plants under study is calcium carbonate (CaCO3), and the usage amount and wash water replacement amount for each plant are as shown in Table 5.

Table 5: Wet Scrubber Operation Data

Factory	Neutralizing agent usage amount [kg/month]	Neutralizing agent cost [1,000 won/month]	Cleaning water replacement amount [ton/month]
Plant A	116,220	14,760	2,730
Plant B	376,830	32,400	4,500
Plant C	118,464	16,584	3,305
Plant D	436,733	37,559	7,500

The average concentration of acid pollutants emitted from the chimney TMS (automatic chimney pollutant measuring instrument) during the study period is as shown in Table 6.

Table 6: Low-pressure turbine electricity savings

Concentration [ppm]	Plant A	Plant B	Plant C	Plant D
HCl	0	0.87	0.12	0.34
SOx	0.2	1.13	0.77	1.19

Since the concentration of pollutants emitted from the TMS is treated with a liquid neutralizing agent (sodium carbonate) and water in the Wet Scrubber for gases emitted from the Dry Reaction (DR) and Bag Filter, and the pH of the Wet Scrubber in each plant is automatically set to 4–6 to control the amount of liquid neutralizing agent injected and the washing water replacement, pH and the washing water replacement ratio were not used as factors to directly compare the efficiency of the neutralizing agent injected in the DR in this study.

3.3. Relationship with the Amount of Fly Ash Generated

Fly ash generated in waste incineration facilities refers to ash originating from boilers, cyclones, SDRs or DRs, and bag filters. The four plants tested in this study operate fire prevention facilities by injecting a dry neutralizing agent into the duct between the DR and the bag filter, and preventing fires in the DR by controlling the temperature and spraying water. Therefore, this study focused only on fly ash generated from bag filters. Fly ash generated from boilers and cyclones is unrelated to the injection of neutralizing agents, as these facilities operate prior to the injection of such agents.

3.4. Cost-Economic Comparison Subjects and Impacts

To compare the cost-effectiveness of DR neutralizing agents, the relationship between the chemicals used in the Wet Scrubber and the fly ash generated in the Bag Filter is as shown in Table 7.

Table 7: Relationships by Economic Comparison Item

DR Neutralizer Usage	**Bag Filter**	**Wet Scrubber**	
	Fly ash Amount generated	Neutralizer usage	Water usage
When increasing usage	▲	▼	▼
When reducing usage	▼	▲	▲

In this study, water usage is excluded from the comparison items because it accounts for a small portion of the cost, and the economic feasibility is examined by comparing the usage and unit price of each DR neutralizing agent, the amount and unit price of fly ash generated, and the usage and unit price of the neutralizing agent of the Wet Scrubber in proportion to the amount of incineration.

4. Cost-economics Comparison

4.1. DR Neutralizer Ingredient Analysis

The results of the component analysis of baking soda and slaked lime used in the DRs of four factories, commissioned to the Chemical Testing Research Institute using the XRD analysis method, are shown in Table 8.

Since baking soda has the property of absorbing moisture from the air and can cause pipe clogging when absorbed, dehumidified compressed air was used for supply. Additionally, because slaked lime can transform into sodium carbonate when it absorbs carbon dioxide from the air, the study was conducted with a short storage period.

Table 8: Analysis results of neutralizing agent components

Neutralizing agents	**Sodium bicarbonate**	**Slaked lime**
Main ingredients	$NaHCO_3$ 94%	$Ca(OH)_2$ 84.1%
Other ingredients	Other 6%	CaCO3 15.9%
Mole	84g/mol (12mol/Kg)	74g/mol (13.5mol/Kg)

Using Equation (1) and Equation (5), the theoretical amount of HCl removed based on the addition of 1 kg of neutralizing agent is 0.434 kg_{HCl}/kg_{NaHCO_3} and 0.492 $kg_{HCl}/kg_{Ca(OH)_2}$.

When calculating the HCl reaction ratio by converting the component content of the chemicals to 94% for baking soda and 84% for slaked lime, the amount of HCl removed by baking soda can be expressed as 0.408 kg_{HCl}/kg_{NaHCO_3} or 2.45 $kg_{HCl}/kg_{Ca(OH)_2Cl}$.

Also, the amount of HCl removed by slaked lime can be expressed as 0.414 $kg_{HCl}/kg_{Ca(OH)_2}$ or 2.42 $kg_{Ca(OH)_2}/kg_{HCl}$.

To compare the HCl removal rates, the unit amount of baking soda used is divided by the unit amount of slaked lime used and converted into a mole ratio as shown in Equation (9). In other words, it is calculated that 1.14 times more baking soda is consumed to remove the same amount of HCl.

$$\frac{2.45\ kg_{HCl}/kg_{Ca(OH)_2Cl}/12mol/Kg}{2.42\ kg_{Ca(OH)_2}/kg_{HCl}/13.5mol/Kg} = 1.14 \qquad \textbf{(9)}$$

This calculation result was derived solely from the ratios in the reaction equation, without considering the reaction rates or reaction times of slaked lime and baking soda. Therefore, to verify the respective ratios of baking soda and slaked lime in the acid gas neutralization reaction at the actual plant, the fly ash components were analyzed.

4.2. Fly Ash Component Analysis

Based on the study data "Physicochemical characterization and resource recovery potential of hazardous municipal solid waste incineration (MSWI) fly ash and air pollution control (APC) residues in the Netherlands," the theoretical fly ash composition can be estimated as shown in Table 9. In the contents of Table 9, the average content of each fly ash component is indicated in parentheses.

Table 8: Theoretical fly ash components, content

Neutralizing Agent	Ingredient	Content [%wt]	Total
$NaHCO_3$	NaCl	50~90(Average 80)	100
	Na_2SO_4	10~50(Average 20)	
$Ca(OH)_2$	Ca(OH)Cl	50~90(Average 75)	100
	$CaSO_3$	10~30(Average 20)	
	$CaCO_3$	5~10(Average 5)	

4.2.1. Fly ash component analysis results

Table 10 shows the results of measurements and analyses commissioned to the Korea Chemical Testing Institute using XRD analysis on samples collected from bag filters of waste incineration facilities at four factories. The analysis of the samples from the four factories revealed that the reaction rate of baking soda ranged from a minimum of 98% to a maximum of 100%. This can be interpreted to mean that the neutralization reaction rate of baking soda was very high, or that an amount less than necessary for the neutralization reaction was input.

Table 10: Fly ash component analysis results

Factory	Neutralizing Agent	Ingredient	Content [%wt]	Total
Plant A	$NaHCO_3$	NaCl	98.0	100
		KCl	2.0	
Plant B	$NaHCO_3$	NaCl	100.0	100
Plant C	$NaHCO_3$	NaCl	98.3	100
		KCl	1.67	
Plant D	$Ca(OH)_2$	Ca(OH)Cl	76.7	100
		$LaFe_4As_{12}$	9.5	
		NaCl	7.6	
		$LiC1_2$	6.2	

The fact that $Ca(Cl)_2$ was not detected among the fly ash components of Factory D, which used slaked lime, indicates that the neutralization reaction did not proceed completely. Instead, the detection of Ca(OH)Cl, an intermediate product of the slaked lime neutralization reaction, suggests that the slaked lime neutralization reaction proceeds more slowly than that of baking soda. Furthermore, it is necessary to verify the significance of the analyzed components such as $LaFe_4As_{12}$, NaCl, and $LiC1_2$. It is presumed that testing errors occurred because these components cannot be detected when slaked lime is used.

The fact that 76.7% of the Ca(OH)Cl component was found can be interpreted as meaning that most of the quicklime participated in the reaction, or that the actual reaction rate was only about 76.7%. This implies that the amount of neutralizing agent added to the DR in all four plants is small compared to the acid gas.

The fact that Na_2SO_3 and $CaSO_3$ were not detected in any of the facilities using baking soda and quicklime means that SO_2 gas was not generated or was not treated.

Therefore, when interpreting the results of the fly ash component analysis, the theoretical reaction equation is correct as calculated in Equation (9) above. However, it means that it cannot be assumed that baking soda and quicklime participated in the reaction 100% as in Equation (9).

4.2.2. Comparison of fly ash generation amounts

It is determined that, in all four factory incinerators, the amount of acid gas neutralizing agent used was insufficient to adequately treat the acid gas. To interpret the analysis data, the amounts of baking soda and quicklime generated were theoretically compared. In Table 11, the fly ash components were estimated based on the fly ash component analysis results, taking into account the error.

Table 11: Modified fly ash components

Neutralizing Agent	Ingredient	Content [%wt]	Total
$NaHCO_3$	NaCl	98.3	100
	$NaHCO_3$	1.67	
$Ca(OH)_2$	Ca(OH)Cl	76.7	100
	$CaCO_3$	23.3	

Using Equation (1) and (5), the theoretical amount of fly ash produced when the neutralizing agent reacts with HCl based on the input of 1 kg of neutralizing agent is calculated as 0.696 kg_{NaCl}/kg_{NaHCO_3} for baking soda and 1.249 $kg_{Ca(OH)Cl}/kg_{Ca(OH)_2}$ for slaked lime.

Furthermore, by converting the neutralizing agent component content of baking soda 94% and slaked lime 84% in Table 8 to calculate the amount of NaCl produced, the amount of NaCl and Ca(OH)Cl produced by baking soda can be expressed as 0.714 kg_{NaCl}/kg_{NaHCO_3} and 1.209 $kg_{Ca(OH)Cl}/kg_{Ca(OH)_2}$.

To compare the fly ash production ratios of baking soda and slaked lime, the unit fly ash production amount when using baking soda is divided by the unit fly ash production amount when using slaked lime and converted into a mole ratio as shown in Equation (10). The ratio of fly ash generated when using baking soda versus using slaked lime is calculated to be approximately 66% of that of slaked lime.

$$\frac{0.714\ kg_{NaCl}/kg_{NaHCO_3}/12mol/Kg}{1.209\ kg_{Ca(OH)Cl}/kg_{Ca(OH)_2}/13.5mol/Kg} = 0.66 \qquad \textbf{(10)}$$

4.3. Correction of Incineration Volume and Chemical Unit Price

Tables 12, 13, and 14 present the annual average chemical purchase costs (DR, Wet Scrubber) and fly ash consignment treatment costs for the incinerators of four plants in 2025, converted based on the average daily incineration volume, the average purchase unit price of DR neutralizing chemicals, and the purchase unit price of Wet Scrubber neutralizing chemicals, respectively, based on Plant D. Table 15 confirms the relative cost-effectiveness of baking soda and quicklime by comparing the overall neutralizing chemical purchase costs (DR, Wet Scrubber) and fly ash consignment treatment costs.

First, the usage of DR neutralizing chemicals was converted into the amount of waste incinerated, and the unit price of the chemicals purchased by each plant was converted and expressed as a cost.

Table 12: Cost-economics comparison of DR Neutralizing Agent Consumption

Item	Unit	Plant A	Plant B	Plant C	Plant D	Remarks
Incinerator capacity	ton/hr	5.5	5.5	4.0	8.0	
Daily incineration amount	ton/day	128	140	112.54	194.3	
Monthly average consumption	kg/month	68,000	53,000	74,000	92,682	
Average unit price	KRW/kg	365	360	360	320	
①Monthly average cost	1,000KRW/month	24,820	19,080	26,640	29,658	Actual chemical purchase cost (2025)
②Converted average cost	1,000KRW/month	21,760	16,960	23,680	29,658	Applying Sep-2025 unit price (320 KRW/kg)
③Converted average cost	1,000KRW/month	33,031	23,538	40,883	29,658	Converted based on Plant D capacity

The amount of fly ash generated was calculated by converting the fly ash generated by each plant into the incineration volume of Plant D, and then converting it into the unit price of fly ash consignment treatment at Plant D.

In addition, the amount of neutralizing agent used in the Wet Scrubber was converted into the incineration volume of Plant D, and then converted into the purchase unit price of the Wet Scrubber neutralizing agent at Plant D.

When comparing the converted purchase costs related to the use of ③DR neutralizing agents, ⑥converted costs related to the consignment treatment of fly ash, and ⑨converted costs related to the use of Wet Scrubber neutralizing agents, it was analyzed that using baking soda was at least 9.1% to a maximum of 27.8% more cost-effective compared to using slaked lime as a neutralizing agent in DR.

Table 13: Cost-economics comparison of fly ash consignment processing fee

Item	Unit	Plant A	Plant B	Plant C	Plant D	Remarks
Monthly average generation	kg/month	71,928	65,796	69,278	148,315	
Average outsourced treatment unit cost	KRW/kg	210	210	170	170	
④ Monthly average cost	1,000KRW/month	15,104	13,817	11,777	25,213	Actual fly ash treatment cost (1H 2025)
⑤ Converted average cost	1,000 KRW/month	12,227	11,185	11,777	25,213	Applying Plant D treatment unit cost
⑥ Converted average cost	1,000KRW/month	18,561	15,523	20,333	25,213	Converted based on Plant D incineration capacity

Plants B and D adopt a method of injecting more acid gas neutralizing agent into the Wet Scrubber than into the DR, while plants A and C operate their pollution control facilities by using more acid gas neutralizing agent in the DR. When comparing only plants A, B, and C that use the same chemical, it was found that using more neutralizing agent in the DR than in the Wet Scrubber is about % more cost-effective.

When acid gas neutralizing agents are primarily used as DR, the likelihood of de novo resynthesis of dioxins is lowered, which can reduce dioxin emission concentrations in the stack. Dioxin de novo resynthesis is a phenomenon in which chlorinated organic substances are regenerated into dioxins through the action of metal catalysts within fly ash during the cooling process of 250–600°C in incinerators.

This is a major cause of the re-generation of dioxins downstream from those destroyed at high temperatures above 750°C; therefore, high-temperature combustion above 850°C or rapid cooling to below 300°C is required. Additionally, if hydrogen chloride, a precursor, is removed as fly ash, it effectively reduces dioxin emissions.

Table 14: Cost-economics comparison of wet Scrubber neutralizing agent consumption

Item	Unit	Plant A	Plant B	Plant C	Plant D	Remarks
Chemical consumption	kg/month	116,220	376,830	118,464	436,733	
Average unit price	KRW/kg	127	86	140	86	Unit price varies depending on impurity content
⑦ Monthly average cost	thousand KRW/month	14,760	32,400	16,584	37,559	Scrubber chemical cost (1H 2025)
⑧Converted average cost	thousand KRW/month	9,994	32,400	10,187	37,559	Applying Plant D unit price
⑨ Converted average cost	thousand KRW/month	15,171	44,976	17,589	37,559	Converted based on Plant D incineration capacity

Table 15: Total converted cost-economics comparison : Sum of ③ + ⑥ + ⑨ [1,000 KRW/month]

Plant A	Plant B	Plant C	Plant D
66,764	84,038	78,806	92,430

5. Consideration

In this study, economic feasibility was compared assuming that the neutralization reactions of baking soda and slaked lime each reached 100%, and baking soda was found to be approximately 10% more economical than slaked lime. However, as confirmed in many previous studies, baking soda has higher reactivity than slaked lime; therefore, actual economic feasibility may vary significantly when comparing the economics of total acid gas neutralization, depending on the reaction rate of acid gas treatment by type of neutralizing agent in the DR. Although DR is often used as a primary treatment facility in actual incineration facility operations, and it was difficult to verify the reaction rate when a Wet Scrubber is used as a secondary treatment facility—as in the facility studied in this research—it was difficult to make an accurate comparison of economic feasibility and determine the margin of error.

When reviewing the economic feasibility of dry neutralizing agents in waste incineration facilities, the items to be considered cannot be calculated based solely on the amount of chemicals used and the amount of waste generated.

Since this study compared actual incineration facilities, the operators and managers running the equipment differ, the characteristics of each facility vary, and, above all, the management policies and philosophies of the management regarding the operation of environmental facilities also differ. Therefore, when comparing the economic feasibility of waste incineration facilities by site, it is necessary to additionally consider the following items in addition to simply comparing the amount of chemicals used or the amount of incinerated ash generated.

First, the concentration or total amount of pollutants emitted from the incinerator into the atmosphere changes depending on the answer to the question: "Should we operate pollution control facilities solely to comply with emission standards to maximize cost reduction, or should we manage them to efficiently protect the environment in addition to complying with laws and regulations?" Furthermore, the amount of chemicals used in the DR of the incineration facility and the treatment efficiency may change depending on that decision.

Therefore, in order to protect the environment efficiently as well as ensure compliance with regulations, the establishment of internal standards or limits regarding pollutant emission concentrations and quantities by factory or company when discharging environmental pollutants into nature affects research results.

Second, whether the target concentration and quantity for acid gas removal in DR are specifically defined can also influence the economic comparison of different chemicals.

The specific target concentration or quantity for acid gas removal must be set considering factors such as the protection of downstream pollution control facilities in incineration plants and the impact of SCR catalyst poisoning. This is because the maintenance costs of downstream pollution control facilities may be affected by the limit concentration or total quantity of acid gases.

Third, the amount of chemicals injected in downstream pollution control facilities, the wash water replacement cycle, chemical costs for wet absorption towers, chemical costs for wastewater treatment plants, and water quality issues regarding recycled water also affect the economic feasibility of dry neutralization chemicals. If the wash water replaced in wet absorption towers is supplied to the process as recycled water after wastewater treatment, it may have a significant impact on product quality or input.

Furthermore, although the TMS concentrations of exhaust gases from the four incinerators tested in this study remain below permissible emission standards, it is determined that this is due to significant removal by the wet absorption towers, which are downstream pollution control facilities, rather than effective control of acid gases in the DR system. Therefore, further research is needed to add detailed standards regarding the chemical usage, wash water replacement volume, and replacement cycle of the wet absorption towers at each plant.

Fourth, consideration must be given to the durability of pollution control facilities, such as SCR, bag filters, and white smoke reduction equipment, where corrosion caused by acid gases is a concern. Sulfur oxides act as SCR catalyst poisons, and chlorine gas is sensitive to corrosion of metal materials.

Therefore, differences arise in the economic comparison of acid neutralizing agents depending on whether acid gas treatment is operated primarily through DR or through wet scrubbers. If acid gas is to be controlled primarily through wet scrubbers, the impact on the maintenance costs of the white plume reduction system will be significant. This is because the exhaust gas temperature in the white plume reduction system is operated below the acid dew point of sulfuric acid or hydrochloric acid, and thus is directly affected by low-temperature corrosion; consequently, it may be more economical to sufficiently remove acid gas before it enters the system.

Fifth, the possibility of increased chlorine gas concentration and dioxin re-synthesis due to the reduced use of neutralizing agents in the DR system must also be considered.

Since the re-synthesis of dioxins is concentrated in areas where fly ash is generated and downstream of dust collection facilities, the probability of dioxin re-synthesis may increase if hydrogen chloride is not sufficiently removed in the DR or bag filter. In such a case, even if the amount of chemicals used in the DR is reduced, the use of activated carbon and other materials increases, resulting in an actual increase in the amount of neutralization chemicals used in the DR. Ultimately, this can affect the treatment efficiency of each type of chemical.

6. Conclusion

In this study, the reaction characteristics and economic feasibility of sodium bicarbonate and highly reactive quicklime, representative acid gas neutralizing agents used in the dry reaction process of waste incineration facilities, were compared and analyzed based on actual operating data. Synthesizing the research results, the following conclusions can be drawn.

First, based on theoretical chemical equations, quicklime was found to have a lower consumption rate relative to the unit acid gas removal rate than sodium bicarbonate; however, under actual operating conditions, sodium bicarbonate exhibited higher reaction rates and reaction completeness, demonstrating advantageous characteristics in terms of acid gas removal efficiency.

Second, the analysis of fly ash components revealed that sodium bicarbonate mostly reacted completely and existed in the form of sodium chloride, whereas quicklime showed a high proportion of intermediate products, indicating that the reaction did not proceed sufficiently. Consequently, the amount of fly ash generated also tended to decrease when sodium bicarbonate was used compared to quicklime.

Third, a comprehensive comparison of chemical costs, fly ash treatment costs, and neutralization chemical costs for downstream wet scrubbing facilities based on the same incineration volume showed that applying sodium bicarbonate resulted in a reduction of approximately 9–28% in total operating costs, demonstrating relatively superior cost-effectiveness.

Fourth, operating an acid gas treatment strategy centered on DR is expected to have positive effects in terms of environmental stability, such as reducing corrosion and catalyst poisoning in downstream facilities and inhibiting dioxin resynthesis.

However, this study has limitations in that it is difficult to completely exclude the influence of differences in facility-specific operating conditions, management policies, and pollution control facility operation strategies; therefore, further research incorporating long-term operating data and various treatment process conditions is required in the future.

In conclusion, the economic evaluation of acid gas neutralizing agents in waste incineration facilities should be conducted from an integrated perspective that includes reaction efficiency, fly ash characteristics, downstream facility operating costs, and environmental impact, rather than merely comparing unit prices. This study can serve as foundational data for presenting criteria for selecting neutralizing agents in actual industrial settings.

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