THE EFFECT OF THE L/G RATIO ON SO_2 REMOVAL EFFICIENCY IN SEAWATER ABSORPTION COLUMNS

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Abstract

Steam Turbine Power Plants are widely known as one of the primary sources of electricity generation, utilizing coal combustion. However, this process leads to the emission of air pollutants, including sulfur dioxide (SO_2), which is considered harmful. To mitigate this issue, Seawater Flue Gas Desulfurization (SWFGD) has been implemented as a control device to reduce the concentration of SO_2. Previous studies on SWFGD have mainly focused on operational factors such as gas flow rate and liquid flow rate using artificial seawater as the absorbent. However, there is a lack of research on utilizing natural seawater, particularly from Indonesia, as the absorbent. Hence, this study aims to determine the efficiency of SO_2 removal using Indonesia's natural seawater and investigate the influence of varying the L/G (liquid-to-gas) ratio on the overall removal efficiency. The study employed a packed tower reactor with a counter-current flow configuration. The gas concentration of SO_2 used in this study is 1500 ppm, which is adjusted to match the existing conditions in the Steam Turbine Power Plant. The variations in seawater flow rate range from 150 to 250 liters/hour, while the variations in gas flow rate range from 1 to 10 m^3/hour at 30°C. So, the L/G ratio value is within the range of 20.9 to 104.5. The results indicated that an increase in the L/G ratio corresponded to an increase in the total removal efficiency. The highest achieved efficiency reached 98.5%, while the lowest efficiency recorded was 84%.

Keywords: *efficiency, natural seawater, SO_2, Steam Turbine Power Plant, SWFGD*

Introduction

Given the rapid population growth worldwide, including in Indonesia, there is a significant increase in energy demand, particularly electricity. To meet this growing need, Steam Power Plants, which burn coal to generate power, are commonly employed. According to (Bahrin et al., 2015), global coal consumption reached 7.8 billion tons/year (2012), and Indonesia alone accounted for an estimated 80 million tons or 23% of national production. According to the IEA's mid-year Coal Market Update (2023), coal consumption in 2022 rose by 3.3% to 8.3 billion tonnes, setting a new record. Data from the Indonesian Ministry of Energy and Mineral Resources showed that coal consumption in 2022 amounted 193 million tons/year. However, the combustion of coal in these plants emits various air pollutants, with sulfur dioxide (SO_2) being a prominent and hazardous substance. Despite the potential to reduce SO_x emissions, specifically SO_2 and SO_3, by replacing standard coal with low-sulfur content coal, this practice remains uncommon, particularly in Indonesia. The limited availability of low-sulfur coal sources and the higher production costs contribute to its

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infrequent use. Consequently, as many power plants in Indonesia continue to rely on high-sulfur coal, the primary emissions resulting from coal combustion predominantly consist of high-concentration SO_2.

When the concentration of SO_2 in the air exceeds acceptable levels, it poses serious risks to the environment and human health. Therefore, it is crucial to implement measures for controlling air pollution. One effective approach is the installation of air pollution control devices, typically placed before the emission of exhaust gases into the environment through chimneys. These devices play a vital role in minimizing the release of harmful substances, thus ensuring a cleaner and healthier environment.

In general, there are different technologies available for removing sulfur dioxide (SO_2). One widely used technology is absorber technology, particularly the wet absorber type. Wet absorbers use a solution, such as water or other liquids, to absorb SO_2 from the gas phase and transfer it to the liquid phase. This process is commonly known as Flue Gas Desulfurization (FGD) technology.

Over time, the range of solutions used for SO_2 absorption has become more diverse. In Indonesia, where numerous Steam Turbine Power Plants are located near the coast, FGD technology utilizing seawater as the absorbent solution is gaining popularity. A study conducted by (Flagiello et al., 2018) demonstrated that both packed bed and spray tower types of absorber columns, using seawater as the absorbent, achieved high absorption efficiency ranging from 96% to 99% for SO_2 removal.

Furthermore, (Han et al., 2018) discovered that in a spray tower absorber column with two plate stages using artificial seawater, the efficiency of SO_2 removal reached up to 99.7%. These findings highlight the potential of seawater as an absorbent in absorption technology or FGD, considering the achieved high removal efficiencies.

Generally, the L/G ratio, which is the ratio of seawater to gas used, is a crucial parameter in determining the performance of this technology. However, there hasn't been specific research conducted on the performance of SWFGD using Indonesian seawater as the absorbent.

Essentially, the location or source of seawater will influence the absorption process. Considering that variations in the origin of seawater can impact essential characteristics of seawater itself, such as pH, salinity, and alkalinity, seawater plays a dual role as an absorber and as a neutralizer of the acidic SO2 through reactions with its inherent alkalinity components like carbonate and bicarbonate. Consequently, as alkalinity values increase, the neutralization function against the acid formed by the interaction between water and SO2 also intensifies, due to the greater availability of alkalinity components in seawater. Therefore, when alkalinity values rise, seawater undergoes less pH reduction compared to conditions where seawater usage is limited. This prevents seawater from becoming easily saturated and enhances removal efficiency.

As for the role of salinity, the higher the salinity of seawater, the greater the solubility of SO_2 gas in seawater. When the solubility of SO_2 increases in seawater, the mass transfer process of SO_2 from the gas phase to the liquid phase (seawater) also becomes more easily achievable, ultimately resulting in a decrease in the efficiency of SO_2 removal in the gas phase.

The reason behind the increase in solubility with higher seawater salinity lies in the fact that when seawater salinity rises, the concentration of cationic salts in seawater also increases. These ions are capable of reacting with and binding to SO2. These cationic salts include ions such as Ca^+, Mg^+, K^+, or others. As a result, SO_2 will persist in the liquid phase within seawater. Consequently, the gas's solubility directly increases with the rising concentration of these cationic salts, or in other words, it can be concluded that SO_2 solubility increases with higher seawater salinity, leading to improved efficiency. Therefore, it can be inferred from this that the origin of seawater affects the characteristics of seawater itself and influences the overall absorption process results.

Therefore, this study aims to investigate this interesting topic. Additionally, the research will focus on operational conditions such as the inlet SO_2 concentration and seawater conditions that are adjusted to match the typical conditions found in existing Steam Turbine Power Plants. As a result, this study is expected to provide valuable insights for the future application and development of SWFGD technology in Indonesia. Furthermore, this research represents an update on the impact of the L/G ratio on the efficiency of SO_2 removal in the absorption process using seawater.

Research Methodology

This research focuses on examining the impact of varying operating parameters, particularly the flow rate of seawater and gas, expressed as the L/G ratio, on the optimal efficiency of SO_2 absorption. The aim is to determine the ideal L/G ratio that yields the highest efficiency in absorbing SO_2. By exploring different values of these parameters, the study aims to identify the optimal conditions that can maximize absorption efficiency and consequently improve the overall performance of the SO_2 removal process.

Seawater quality

Table 1 below is data on the quality of seawater used as an absorbent. The seawater collected from Pameungpuk Area, Garut, Wst Java, and not from near any turbine power generator, with the assumption that the seawater quality in all of area from Indonesia is more or less the same.

Table 1. Quality of seawater in Indonesia (sample from Pameungpuk Area, Garut)

No.	**Parameters**	**Unit**	**Natural seawater**
1	pH	-	7.88
2	TDS	mg/L	-
3	Alkalinity	mg/L	89.6
4	Salinity	$^{o}/_{oo}$	30.3
5	Sulfate	mg/L	2,556
6	Acidity	mg/L	5.43

Tools and Materials

The reactor diameter used is 0.9 cm, and the height of the packing zone is 0.18 cm. The reactor is constructed using acrylic material. The seawater used is natural seawater rom Pameungpuk Area, Garut with the characteristics mentioned in Table 1. The preparation begins by connecting the seawater storage tank to a pump, which will subsequently deliver the seawater to the top of the absorber column and distribute it throughout the column area via spray nozzles installed at the top of the column. The flow rate or volume of seawater entering the system will be regulated using a flow meter. Meanwhile, the gas will be introduced from the bottom of the column using a perforated pipe to ensure a more uniform distribution of gas across the entire surface area of the absorber column.

In this study, 100% pure SO_2 gas will be used, which means the concentration of SO_2 gas is 1,000,000 ppm. However, since the required concentration of SO_2 gas for this research is 1400 – 1500 ppm, the 100% pure SO_2 gas needs to be diluted using a gas mixer with regular ambient air. The ambient air is drawn in using a compressor and then directed toward the gas mixing chamber. In the mixing chamber, the SO_2 gas and ambient air are mixed in predetermined ratios based on calculations conducted by the researchers before the experiment. Then, Figure 1 below depicts the schematic of the absorber reactor used.

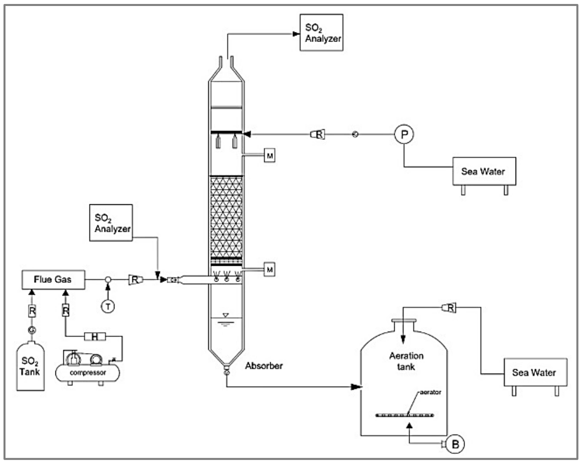

Figure 1. Absorber reactor

To measure the concentration of SO_2 at the inlet and outlet of the reactor, an SO_2 analyzer of the SKY2000 type is used. The measurable concentration range using this instrument is between 0 to 2000 ppm, and the gas temperature conditions range from 0 to 50°C. The SO_2 concentration measurement is performed at intervals of 5 seconds for a duration of 10 minutes or longer to obtain measurement results that are less fluctuating. By taking measurements over a longer period, it allows for a more comprehensive analysis of the average concentration, reducing the impact of short-term fluctuations and providing a more reliable representation of the overall SO_2 levels during that time frame. Furthermore, the reaction between SO_2 and seawater components is considered a relatively fast reaction. Therefore, a 10-minute time limit is imposed to prevent saturation conditions where seawater can no longer effectively absorb SO_2 in its gaseous form.

Data processing

The removal efficiency and L/G ratio can then be calculated using Eq (1) and (2).

$$\text{L/G ratio} = \frac{\text{liquid flow rate (seawater)}}{\text{SO2 gas flow rate}} \qquad (1)$$

$$\%\ \text{efficiency} = \frac{\text{Cin} - \text{Cout}}{\text{Cin}} \times 100\% \qquad (2)$$

Where C_{in} is inlet concentration of SO_2 (ppm) and C_{out} is outlet concentration of SO_2 (ppm).

Result and Discussion

The combination of different liquid flow rates and gas flow rates will result in different L/G ratios. For this study, the L/G ratio values used range from 20.9 to 104.5. This range is obtained by initially determining the range of liquid flow rate and gas flow rate values while considering the L/G ratio conditions used in one of the existing power plants, which had a value of 50 as a reference. From this value, it is then varied both upwards and downwards to observe how the L/G ratio affects the removal efficiency.

Figure 2, 3, 4, and 5 below shows the graph comparing the obtained removal efficiency for each varying L/G ratio. In While in Figure 5, it is clear that the efficiency obtained is directly proportional to the L/G ratio value. The higher the L/G ratio value, the higher the overall removal efficiency. Then, in Figures 2, 3, and 4, data is presented regarding the three comparison graphs on how the concentration changes between the inlet and outlet points of the absorber column and its influence on the removal efficiency.

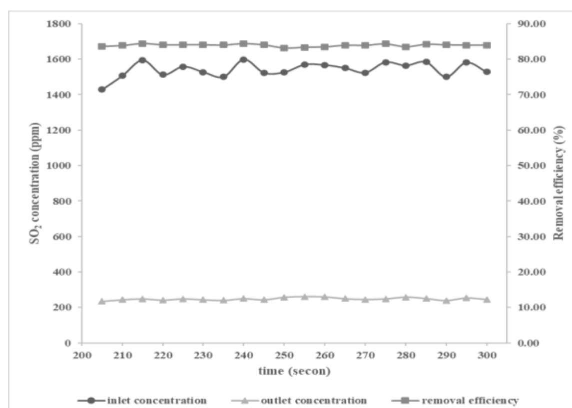

Figure 2. Comparison graph of inlet concentration, outlet concentration, and removal efficiency at an L/G ratio of 20.9

In Figure 2, with an L/G ratio value of 20.9, the concentration of SO_2 at the outlet point ranges from 200 to 300 ppm, with an efficiency ranging from 80 to 85%. Meanwhile, in Figure 3, with an L/G ratio value of 55.8, it is found that the concentration of SO_2 at the outlet point ranges from 100 to 200 ppm, while the removal efficiency increases to a range of 90 to 95%. Lastly, in Figure 4, which displays the concentration profile at an L/G ratio value of 104.5, it is observed that the concentration of SO_2 at the outlet point ranges from 5 to 20 ppm, and the range of removal efficiency lies between 98 and 100%.

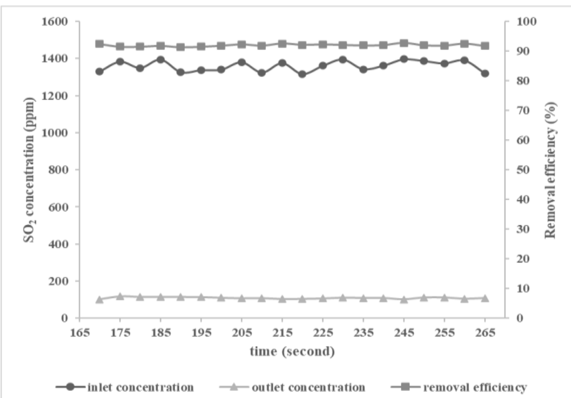

Figure 3. Comparison graph of inlet concentration, outlet concentration, and removal efficiency at an L/G ratio of 55.8

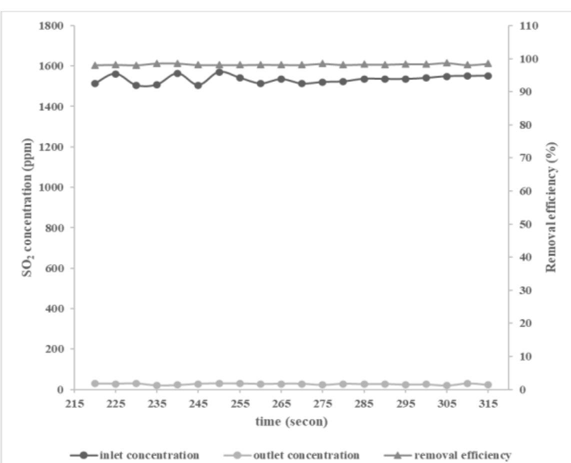

Figure 4. Comparison graph of inlet concentration, outlet concentration, and removal efficiency at an L/G ratio of 104.5

From these results, it can be seen that increasing the L/G ratio leads to a greater decrease in concentration, resulting in a lower concentration of SO_2 exiting the absorber column and measured at the outlet point. As a result, the removal efficiency increases. These results can be understood because a higher L/G ratio implies that more liquid absorbent is used to absorb SO_2 from the gas. Therefore, the greater the amount of SO_2 that can be absorbed in the same contact time, the more SO_2 can be absorbed by the seawater absorbent, resulting in higher removal efficiency. A high L/G ratio also indicates that the total contact surface area between the gas and liquid will be larger. Hence, the opportunity for these two phases to come into contact and for mass transfer of SO_2 from the gas phase to the liquid phase will also be higher. Consequently, the removal efficiency will increase.

Most previous studies have used artificial seawater as the absorbent, making it challenging to directly compare their results with this study. However, based on (Van Duc Long et al., 2021), who used artificial seawater for the absorption process with L/G ratio values ranging from 4 to 8 kg/kg, it was found that higher L/G values resulted in increased removal efficiency. Furthermore, according to (Flagiello et al., 2018), who used natural seawater for absorption with a liquid-to-gas ratio between 1.06 and 3.44 kg/kg, removal efficiency could reach up to 80%. The low L/G ratio values achieving high efficiency are likely due to the high salinity of seawater, allowing for significant removal efficiency even with a limited amount of seawater.

The tall and elongated design of the absorber column provides an opportunity for SO_2 and species in seawater to react. As a result, absorption occurs gradually from the bottom of the column to the top. Therefore, when measured, the concentration of SO_2 in the gas at the top of the column will be lower because SO_2 has been absorbed and transferred to the liquid phase (seawater) and reacted with alkaline species in seawater. The common reaction that occurs in the SWFGD process is illustrated in Figure 5 as follows.

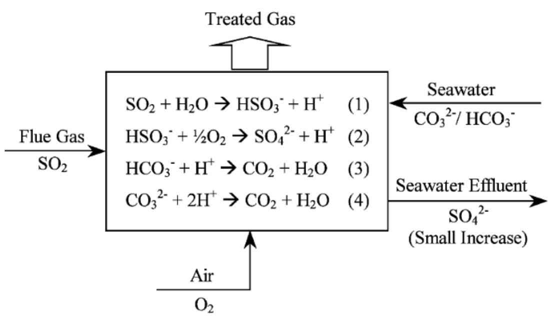

Figure 5. The chemical reactions that occur in an SWFGD system (Oikawa et al., 2003)

In the upper section of the absorber column, the gas-phase concentration of SO_2 decreases due to absorption into the liquid phase. Within the liquid phase, SO_2 undergoes reactions and transforms into sulfite, bisulfite, and sulfate, as illustrated in Figure 5. Additionally, in seawater, the reaction between bisulfite and seawater alkalinity occurs, as depicted in reaction (3). Alkalinity is represented by the bicarbonate (HCO_3^-) function, which holds a significant influence on seawater. Hence, under similar conditions, the concentration of sulfate in seawater increases as the gas-phase concentration of SO_2 decreases. To provide further clarity, Figure 5 portrays Reaction (1) as the formation of bisulfite from dissolved SO_2. Reaction (2) represents the dissociation of hydrogen sulfate into sulfate after the dissociation of bisulfite into sulfite. Finally, reactions (3) and (4) indicate the neutralization of the formed bisulfite using seawater.

As seen in Figure 6, the highest efficiency occurs at the highest L/G ratio value of 104.5, where the efficiency can reach up to 98,5%. Conversely, the lowest removal efficiency occurs when the L/G ratio is also the lowest among all the L/G ratios used. The lowest efficiency occurs at an L/G ratio of 20.9, with a range of obtained efficiencies ranging around 84%.

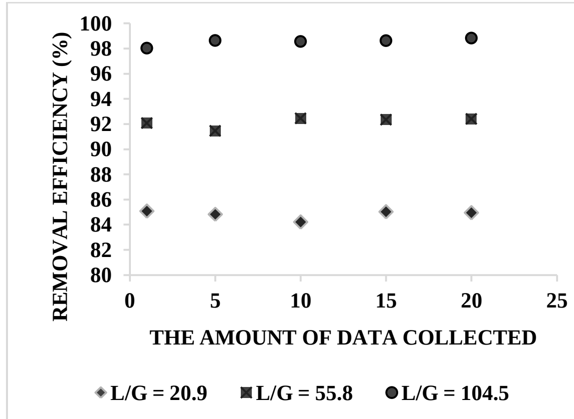

Figure 6. The difference in removal efficiency values based on variations in the L/G ratio.

This result can be understood considering that sing a higher L/G (liquid-to-gas) ratio involves utilizing a greater amount of liquid absorbent, like seawater, to trap and absorb SO_2 from the gas. This increased quantity of absorbent enhances the surface area available for gas-liquid interaction, leading to a more effective absorption of SO_2. Consequently, a higher L/G ratio enhances the chances for SO_2 to react with the seawater absorbent, thereby improving the overall efficiency of removing SO_2 from the gas stream.

Apart from the L/G ratio, which affects the height of the transfer zone in the absorber column, the increased removal efficiency resulting from higher L/G values is also attributed to the chemical reactions between seawater components and the absorbed SO_2 in the liquid phase (seawater). Chemical species responsible for seawater alkalinity, such as carbonate (HCO_3^-) and bicarbonate (CO_3^{2-}), act as catalysts in the absorption of SO_2, promoting the formation of dissociation products of $H_2SO_{3(aq)}$, the hydrated form of dissolved SO_2.

The absorption reaction of SO_2 follows the illustrated process in Figure 5 (Oikawa et al., 2003). Thus, higher alkalinity levels in a solution enhance the performance and absorption of SO_2. Further analysis reveals that Indonesian seawater, characterized in Table 1, exhibits an alkalinity of 89.6 mg/L. Consequently, with such high alkalinity, the solubility of SO_2 becomes significantly elevated. Nevertheless, according to (Flagiello et al., 2021), seawater alkalinity exceeding a threshold of 33 – 37 g/L becomes highly corrosive. Therefore, caution is advised against excessively high L/G ratios since they entail increased liquid usage, which raises the risk of rapid corrosion, particularly in infrastructure like pipelines.

On the other hand, according to (Flagiello et al., 2018), who also conducted experiments on the influence of L/G ratio values on removal efficiency using various types of absorbents, the results showed that for seawater absorbent, the removal efficiency would increase with an increase in the L/G ratio. The range of removal efficiencies obtained for an inlet SO_2 concentration of 2000 ppm was between 20% and 75% with L/G ratio values ranging from 1 to 5.

Another study conducted by (Lee & Che, 2011) also examined the effect of L/G ratio values on SO_2 removal efficiency. In their research, they found that for L/G ratio values ranging from 5 to 20, the removal efficiency ranged from 96% to 99% with an inlet SO_2 concentration of 150 ppm. This study also concluded that higher L/G values lead to increased removal efficiency. Both studies align with the results obtained in this research. In this study, with an inlet SO_2 concentration ranging from 1400 to 1500 ppm and L/G ratio values ranging from 20 to 104.5, the range of removal efficiency obtained was 84% to 98.5%. Then, if the results of this research are compared to one of the existing Steam Turbine Power Plants in Indonesia, where the L/G ratio used is 59 and the obtained efficiency is 96% (Hitachi & Systems, 2019), the results of this research are considered valid because, at L/G values of 55.8, the range of removal efficiency is about 85% to 90%.

Based on Figures 2, 3, and 4, the optimum efficiency occurs at the highest L/G ratio. Then, based on the graphs, a relationship between the overall removal efficiency and the L/G ratio is established, resulting in the following Figure 7.

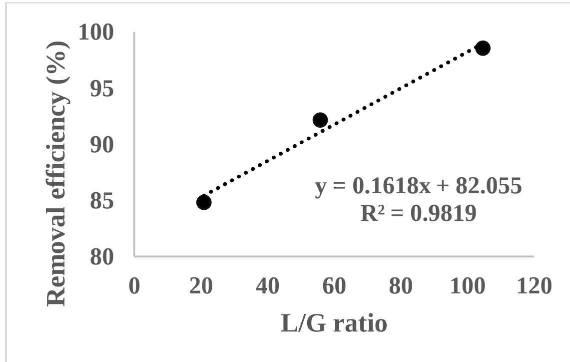

Figure 7. The relationship between the L/G ratio and overall removal efficiency

Based on Figure 7, there is a linear relationship between the L/G ratio and the removal efficiency. As the L/G ratio increases, the resulting removal efficiency also increases. The relationship between the two can be represented by a linear equation derived from the graph, with a slope value of 0.1618 and a correlation coefficient of 0.9818. The positive and close-to-1 correlation coefficient indicates a strong positive linear relationship between the L/G ratio and the overall removal efficiency. This means that when one variable increases, the other variable tends to increase proportionally.

Conclusions

Based on the research results, the average removal efficiency obtained in the absorption process using seawater ranges from 84% to 98.5%. The highest removal efficiency occurs at the highest L/G ratio value of 104.5, with a removal efficiency of 100%. On the other hand, the lowest efficiency occurs at an L/G ratio of 20.9, with a corresponding efficiency of 84%. As the L/G ratio increases, more seawater is utilized, leading to a higher chance of contact between SO_2 gas and seawater. Consequently, the removal efficiency will also increase along with the increase in the L/G ratio. During the contact, SO_2 in the gas phase will transfer into the liquid phase and subsequently react with components of seawater such as carbonate and bicarbonate.

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