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Effect of Operating Parameters on Sulfur Dioxide Gas Removal in the Spray Tower: An Investigation

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Abstract

Introduction: Sulfur dioxide (SO_2) is a major air pollutant with severe health and environmental impacts. Spray towers are widely used in flue gas desulfurization (FGD) systems; therefore, optimizing their operational parameters is crucial for enhancing SO_2 removal efficiency.

Methods: This study investigated the effects of liquid flow rate (4–6 L/min), gas flow rate (105–158 ft³/min), inlet SO_2 concentration (60–120 ppm), nozzle type, and the number of nozzles on the removal efficiency of sulfur dioxide gas using a spray tower (1.38 m in height, 0.25 m in diameter). The experiments were designed using Response Surface Methodology (RSM) through Design-Expert software.

Results: The highest removal efficiency (96%) was achieved with the SS80 Berto nozzle, liquid flow rate of 6 L/min, gas flow rate of 105 ft³/min, three nozzles, and an inlet SO_2 concentration of 60 ppm. Gas flow rate and inlet concentration negatively impacted efficiency, while liquid flow rate and the number of nozzles had a positive effect ($P < 0.001$).

Conclusion: Optimizing operational parameters, particularly nozzle type and liquid flow rate, significantly improves spray tower performance for SO_2 removal.

Keywords: Sulfur dioxide, Air pollution, Gas-liquid systems, Environmental monitoring

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Introduction

Air pollution is one of the most pressing global challenges, with far-reaching consequences for human health, ecosystems, and climate stability. It is widely acknowledged that particulate matter (PM), ground-level ozone (O_3), carbon monoxide (CO), and sulfur oxides (SO_x) are among the primary air pollutants contributing to environmental degradation and public health crises (1). Sulfur dioxide (SO_2), a significant component of SO_x, is predominantly released from anthropogenic sources, such as coal combustion, petroleum refining, metal smelting, and chemical manufacturing processes (2). The harmful effects of SO_2 emissions extend across multiple domains. In the atmosphere, SO_2 reacts with water vapor to form acid rain, which damages forests, soils, and aquatic systems while also corroding infrastructure (3). Furthermore, SO_2 contributes to the formation of secondary particulate matter, a leading cause of respiratory and cardiovascular diseases (4). In addition to its ecological impacts, prolonged exposure to SO_2 has been linked to bronchial constriction, shortness of breath, and chronic respiratory conditions, with acute exposures potentially leading to life-threatening complications (5). Given these health risks, regulatory agencies worldwide have established stringent exposure limits. The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a short-term exposure limit (STEL) of 0.25 ppm for SO_2, while the Occupational Safety and Health Administration (OSHA) sets an 8-hour permissible exposure limit (PEL) of 5 ppm (6). Iran has adopted the same STEL value of 0.25 ppm based on the ACGIH guidelines to limit occupational exposures (7). The efforts to curb SO_2 emissions have led to the development of various technological solutions, among which flue gas desulfurization (FGD) systems are particularly effective. FGD processes involve the removal of SO_2 from industrial exhaust gases using physical, chemical, or biological methods (8). Wet scrubbers, including spray towers, are commonly employed within FGD systems due to their operational simplicity, high removal efficiency, and adaptability to different gas flow conditions (9). Spray towers function by introducing polluted gas into a chamber where liquid droplets, sprayed from nozzles, interact with the gas in a countercurrent flow configuration. This interaction facilitates the mass transfer of SO_2 from the gas phase to the liquid phase, where it reacts to form stable compounds such as sulfates (10). The efficiency of this process is influenced by several operational parameters, including gas flow rate, liquid flow rate, nozzle type, droplet size, and the number of nozzles (11). The liquid-to-gas ratio (L/G) is a critical determinant of spray tower performance. An optimal L/G ratio ensures sufficient contact between the gas and liquid phases, thereby maximizing the absorption of SO_2 (12). However, increasing the liquid flow rate beyond a certain threshold can lead to higher operational costs and water consumption, necessitating careful optimization of process parameters (13). Nozzle design plays a pivotal role in spray tower efficiency. The type, size, and spray pattern of the nozzle determine the droplet size distribution, which in turn affects the surface area available for gas-liquid interaction (14). For instance, smaller droplets provide a larger surface area for absorption but may be prone to drift and uneven distribution (15). Studies have shown that conical nozzles and flat fan nozzles produce droplet spectra that enhance SO_2 removal, particularly under high gas flow conditions (16). The chemical composition of the scrubbing liquid further influences the absorption process. Alkaline solutions, such as those containing sodium hydroxide (NaOH), significantly improve the removal efficiency by neutralizing acidic SO_2 to form sodium sulfite and sulfate (17). The overall reaction taking place in the scrubber is shown in Equation 1. The addition of oxidizing agents like hydrogen peroxide can also enhance the absorption kinetics (18). Despite these technological advancements, several challenges persist in achieving optimal SO_2 removal. High inlet gas concentrations, variable gas flow rates, and limited liquid capacity can reduce the absorption efficiency of spray towers (11,19). Additionally, operational constraints such as pressure drops, maintenance requirements, and byproduct management complicate the implementation of FGD systems in diverse industrial settings (20).

$$SO2 + 2OH- \rightarrow SO32- + H2O \quad (1)$$

In response to these challenges, this study investigated the effects of key operational parameters—gas flow rate, liquid flow rate, inlet gas concentration, nozzle type, and the number of nozzles—on the removal efficiency of SO_2 in a spray tower. Using a central composite design (CCD) approach and response surface methodology (RSM), the study aimed to optimize these parameters to achieve maximum removal efficiency while minimizing resource consumption (21). The significance of this research lies in its potential to guide industries in designing and operating spray towers that meet stringent environmental regulations. By providing a comprehensive understanding of the interplay between operational parameters, the findings can inform the development of more efficient and cost-effective SO_2 control technologies (22). Additionally, the insights gained from this study can contribute to the broader field of air pollution control, advancing efforts to mitigate the environmental and health impacts of industrial emissions (23). The effectiveness of the RSM-CCD methodology in optimizing environmental processes has also been demonstrated in recent studies involving the adsorption of contaminants from water, showing excellent model fit and predictive performance (24).

Several previous studies have explored the performance of spray towers under varying operational parameters. The efficiency of different nozzle types was evaluated, and it was demonstrated that full-cone nozzles provided superior SO_2 removal under high gas flow conditions (11). Computational fluid dynamics (CFD) simulations have also been used to optimize spray tower design, highlighting the critical role of liquid distribution and droplet size (13). In a separate study conducted on a rotating packed bed system, it was reported that modifying the gas flow rate and adjusting the chemical composition of the scrubbing solution can significantly improve absorption efficiency; the findings offer valuable insights for spray-based scrubbers as well (16). However, most prior investigations have been limited to single-variable analyses or fixed nozzle configurations. The present study addressed this gap by systematically examining multiple parameters, including nozzle type, number of nozzles, and flow conditions, through response surface methodology (RSM) to identify optimal configurations for SO_2 removal.

Materials and Methods

The analysis method used for this study involved a systematic experimental design and rigorous statistical evaluation to optimize the operational parameters of the spray tower for sulfur dioxide (SO_2) removal. The steps undertaken are outlined below:

Experimental Design

The study employed the Central Composite Design (CCD) approach, a widely used method in response surface methodology (RSM), to evaluate the effects of independent variables on SO_2 removal efficiency. The key parameters investigated in this study are presented in Table 1.

A total of 90 experiments were performed based on the CCD to ensure a comprehensive understanding of the interactions among these factors.

Spray Tower Setup

The spray tower used in the experiments had the following specifications:

- **Height:** 1.38 meters
- **Internal diameter:** 0.25 meters

Table 1. Key input variables, levels, and analysis of variance for removal efficiency

Response	Source	Unit	Levels/Coded Values	Sum of Squares	df	Mean Square	F-value	*P*-value	
Efficiency	Model			22770.40	20	1138.52	32.19	<0.0001	Significant
	A-liquid flow rate	L/min	4 – 5 – 6	746.68	1	746.68	21.11	<0.0001	
	B-gas flow rate	CFM	105 – 132 – 158	193.07	1	193.07	5.46	0.0224	
	C-concentration	ppm	60 – 90 – 120	2079.48	1	2079.48	58.80	<0.0001	
	D-nozzle number	—	SS30 Berto SS80 Berto 2500-micron	3489.68	1	3489.68	98.67	<0.0001	
	E-nozzle type	—	1 – 2 – 3	13358.99	2	6679.49	188.87	<0.0001	
	AB			0.1244	1	0.1244	0.0035	0.9529	
	AC			7.76	1	7.76	0.2194	0.6410	
	AD			2.76	1	2.76	0.0779	0.7810	
	AE			8.89	2	4.45	0.1257	0.8821	
	BC			11.08	1	11.08	0.3134	0.5774	
	BD			1.31	1	1.31	0.0371	0.8479	
	BE			8.84	2	4.42	0.1249	0.8827	
	CD			475.65	1	475.65	13.45	0.0005	
	CE			955.43	2	477.72	13.51	<0.0001	
	DE			1430.65	2	715.33	20.23	<0.0001	
	Residual			2440.25	69	35.37			
	Lack of Fit			2113.25	54	39.13	1.80	0.1059	Not significant
	Pure Error			327.00	15	21.80			
	Cor Total			25210.64	89				
	$R^2=0.9032$, $R^2_{Adjusted}=0.8751$, $R^2_{Predicted}=0.8371$, Adeq Precision=26.3939.								

- **Airflow generation:** Controlled by a variable-speed fan with a maximum capacity of 240 volts and 67 liters per second.
- **Liquid flow:** Delivered using a stainless-steel electro-pump (CDLF2-13-M). The specifications of this pump are listed in Table 2.

Three types of solid cone nozzles were used, each producing distinct droplet size distributions to evaluate the impact of nozzle type and quantity on SO_2 removal efficiency (Table 1).

Table 2. Electro-Pump Characterization

Model	CDLF2-13-M
Speed (RPM)	2825
Voltage (V)	220
Power (W)	1500
Current (A)	1/9
Frequency (Hz)	50
Maximum Flow (m^3/h)	5

SO_2 Injection and Measurement

Sulfur dioxide gas was introduced into the spray tower at controlled concentrations (60, 90, and 120 ppm) using a calibrated gas regulator. Concentrations at the inlet and outlet of the tower were measured using a high-precision Testo 350-XL gas analyzer.

The removal efficiency (%) was calculated using the following formula:

$$\text{Removal Efficiency }(\%)=\frac{(\textit{outlet gas concentration}-\textit{inlet gas concentration})}{\textit{inlet gas concentration}}\times 100$$

Optimization and Statistical Analysis

The experimental results were analyzed using Design Expert software (version 26), which provides tools for model fitting, response surface plotting, and optimization. The key steps included:

Model Fitting

A quadratic polynomial equation was developed for each nozzle type to predict SO_2 removal efficiency.

Analysis of Variance (ANOVA)

Statistical significance of the model and individual terms was evaluated. Statistical significant level was considered at $P<0.05$.

Response Surface Analysis

Three-dimensional plots were generated to visualize the interactions between variables and their effects on removal efficiency.

Model Validation

The accuracy of the regression models was assessed using R^2, adjusted R^2, and predicted R^2. A lack-of-fit test was conducted to ensure the model adequately represented the experimental data.

Residual Analysis

The residuals (differences between observed and predicted values) were analyzed to confirm the assumptions of normality and homoscedasticity. Plots of residuals versus predicted values showed random scatter, indicating a good fit of the model.

Results

In this study, the Central Composite Design (CCD) method was employed to optimize operational parameters in a spray tower for the removal of sulfur dioxide gas. A total of 90 experiments were conducted based on the experimental design (Table 3) to evaluate the removal efficiency. Design Expert software proposed a mathematical model for each nozzle type used in the study. It recommended a two-factor polynomial equation to predict the removal efficiency, allowing the experimental data to align closely with the response variable. The equations, expressed in terms of actual values, for the ss30 Berto nozzle, ss80 Berto nozzle, and 2500-micron nozzle are provided below as equations 2, 3, and 4, respectively:

$$\text{Efficiency} = 68.19 + 3.3A + 0.002363B - 0.27C - 0.148D + 0.105CD \quad (2)$$

$$\text{Efficiency} = 101.45 + 2.33A - 0.0102B - 0.345C - 5.27D + 0.105CD \quad (3)$$

$$\text{Efficiency} = 71.64 + 2.6A - 0.034B - 0.6C + 7.26D + 0.105CD \quad (4)$$

Table 1 presents the model fitting method based on ANOVA. In this table, A, B, C, D, and E correspond to liquid volume flow, gas volume flow, concentration of gas entering the tower, number of nozzles, and nozzle type, respectively. *P*-values less than 0.05 indicate significant model conditions, while *P*-values greater than 0.1 indicate non-significance. In this study, a *P*-value < 0.0001 confirms that the models are significant with a confidence level above 95%. The experimental data showed that there is only a 0.01% probability, which is due to noise. The R^2 was close to 1 (0.9032) for removal efficiency, indicating a good fit of the regression model and accounting for 90.32% of the observed variability in sulfur dioxide removal efficiency. The adjusted Adj-R^2, another index used to assess the model fit, was 0.8751 in this study. As shown in Table 1, the difference between R^2 and Adj-R^2 is less than 0.2, indicating that the model accurately predicts the corresponding response variable value (Table 1).

Figure 1 illustrates the schematic diagram of the gas scrubbing system. The main components, including the spray tower, nozzles, variable-speed fan, inline electropump, sodium hydroxide solution tank, pressure gauge, and inlet/outlet paths, are clearly shown. The system is designed to allow the absorbent solution to be sprayed through the nozzles within the tower, enabling effective contact between the gas and liquid phases for pollutant removal. The variable-speed fan ensures a controlled flow of gas into the system, which, after treatment, exits from the top of the tower.

After confirming the fitness of the model, its adequacy was examined to ensure it provides a suitable estimate of the real system. This was assessed through residual analysis and measurement of lack of fit. Figure 2 displays the normal probability diagram obtained from the ANOVA analysis. This shows a linear trend, suggesting that normality is not a significant issue. Therefore, no transformation is needed for the responses (Figure 2).

Figure 3 illustrates the plot of studentized residuals against predicted values for the response variable "removal efficiency". The random scatter of the residuals indicates that the true observations are consistent across all response values (Figure 3).

Figure 4 depicts the predicted values plotted against

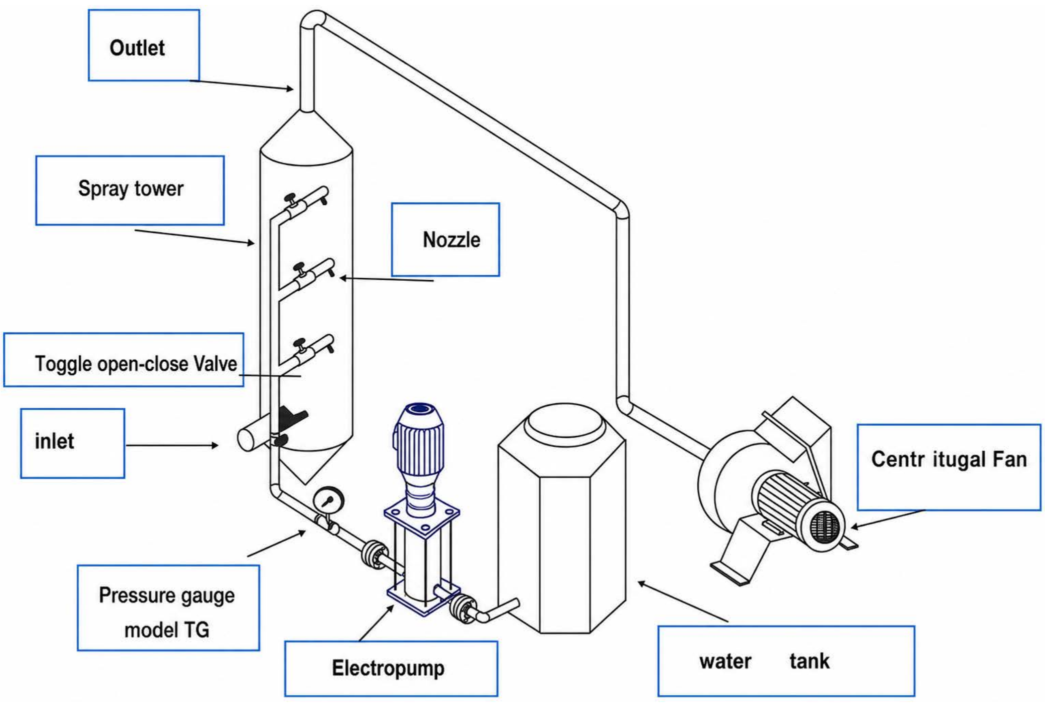

Figure 1. Schematic diagram of the system

Table 3. Experimental Results Designed Using Design-Expert Software

Test Number	Liquid Flow Rate (L/min)	Gas Flow Rate (ft^3/min)	Inlet SO_2 Concentration (ppm)	Number of Nozzles	Nozzle Type	Removal Efficiency (%)	Test Number	Liquid Flow Rate (L/min)	Gas Flow Rate (ft^3/min)	Inlet SO_2 Concentration (ppm)	Number of Nozzles	Nozzle Type	Removal Efficiency (%)
1	6	105	60	1	80	90	24	5	132	90	3	30	85
2	5	158	90	2	80	83	25	6	105	60	1	2500	66
3	6	105	120	1	2500	25	26	4	105	120	3	2500	61
4	6	158	120	3	2500	65	27	5	132	120	2	2500	60
5	5	132	90	1	80	87	28	5	105	90	2	80	89
6	5	132	90	1	2500	25.3	29	5	105	90	2	2500	60
7	5	158	90	2	30	72	30	6	158	120	3	30	2/89
8	5	132	60	2	30	78	31	6	158	60	3	80	94
9	5	132	90	2	2500	60	32	6	105	60	3	30	90
10	5	132	60	2	80	90	33	5	132	90	2	80	2/85
11	4	105	120	1	80	78	34	5	132	90	2	80	83
12	5	132	90	2	80	85	35	4	158	60	1	30	69
13	4	105	60	3	2500	76	36	6	158	60	3	2500	7/70
14	6	105	120	3	2500	68	37	4	158	60	3	30	2/81
15	4	132	90	2	30	68	38	5	132	90	2	80	82
16	5	132	120	2	80	86.2	39	5	132	120	2	30	67
17	6	105	60	3	80	96	40	6	158	60	1	2500	4/64
18	5	132	90	3	2500	68	42	4	132	90	2	2500	52
19	5	132	90	2	30	70	43	6	158	60	3	30	88
20	4	158	60	1	2500	58	44	4	158	60	1	80	1/85
21	4	158	60	3	2500	65.6	45	4	105	60	1	2500	56
22	5	132	90	2	2500	63	46	6	105	120	1	80	84
23	4	105	60	3	30	84	47	4	158	120	1	30	60

Table 3. Continued.

Test Number	Liquid Flow Rate (L/min)	Gas Flow Rate (ft³/min)	Inlet SO_2 Concentration (ppm)	Number of Nozzles	Nozzle Type	Removal Efficiency (%)	Test Number	Liquid Flow Rate (L/min)	Gas Flow Rate (ft³/min)	Inlet SO_2 Concentration (ppm)	Number of Nozzles	Nozzle Type	Removal Efficiency (%)
47	4	158	120	1	30	60	70	5	132	90	2	30	72
48	5	132	90	2	2500	64	71	4	105	120	3	80	83
49	4	158	120	1	2500	14	72	4	105	120	3	30	7/83
50	6	132	90	2	80	5/85	73	5	132	90	2	30	3/72
51	6	105	60	3	2500	1/78	74	4	105	60	1	80	87
52	6	105	120	3	80	87	75	6	158	120	1	2500	2/18
53	4	105	60	1	30	70	76	6	158	120	3	80	84
54	6	105	120	1	30	8/76	77	5	105	90	2	30	73
55	4	105	120	1	2500	3/19	78	5	132	90	2	2500	68
56	5	132	90	1	30	5/73	79	5	132	90	2	80	3/87
57	6	105	120	3	30	90	80	5	132	90	2	2500	50
58	5	132	90	2	80	3/87	81	6	132	90	2	2500	69
59	4	158	120	3	80	8/76	82	6	158	120	1	80	79
60	6	158	120	1	30	7/69	83	5	132	90	2	30	2/68
61	6	105	60	1	30	2/79	84	5	132	90	3	80	90
62	4	105	60	3	80	90	85	4	158	120	3	30	1/78
63	5	132	90	2	2500	50	86	6	158	60	1	30	77
64	5	132	60	2	2500	70	87	6	158	60	1	80	89
65	5	132	90	2	30	72	88	5	132	90	2	30	2/68
66	5	158	90	2	2500	53	89	4	105	120	1	30	63
67	4	132	90	2	80	68	90	4	158	120	3	2500	2/57
68	6	132	90	2	30	74							
69	4	158	60	3	80	89							

the actual values. This shows the predicted values for the removal efficiency of sulfur dioxide gas from the spray tower plotted against the experimental (actual) values. The points are scattered around the regression line, indicating a strong agreement between the predicted and experimental values (Figure 4).

Based on Table 1, the F-value for the lack of fit of the response variable is 1.80, indicating that the lack of fit for the model is not significant compared to the net error.

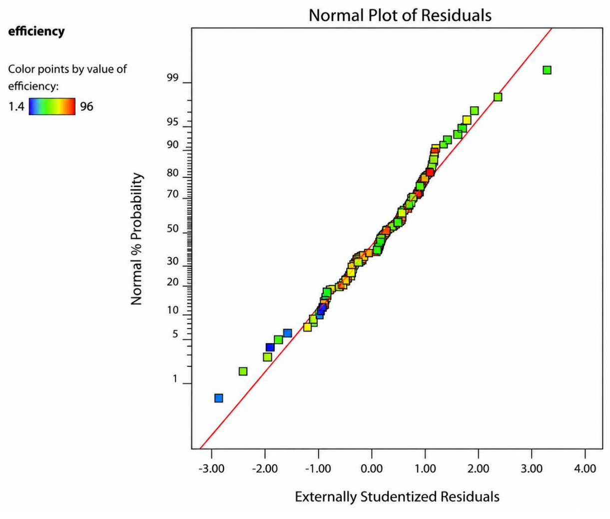

Figure 2. Probability Distribution Chart for Efficiency

Additionally, there is a 10.59% probability of observing such an F-value for disproportion. Although the model does not show a significant lack of fit, it is still important to monitor for any potential issues with the model fit.

Replication and Error Minimization

Key experiments were repeated three times under optimal conditions suggested by the software to verify reproducibility. The average deviation between predicted and experimental efficiencies was within ± 2%.

Optimization of Experimental Conditions Using Design-Expert

Design-Expert software can predict the optimal combinations of input variables to achieve the maximum, minimum, or a specific value of the response variable.

After conducting the preliminary experiments, optimization was performed using Design-Expert to determine the conditions required to achieve the desired SO_2 removal efficiency. Each operational parameter of the spray tower has a distinct effect on the response variable; therefore, in the software's optimization settings, the response variable was set to the "within range" mode rather than to minimum or maximum values. Table 4 presents selected proposed solutions at different required levels of the response variable, with all solutions assigned a desirability of 1, an importance of 3, and both upper and

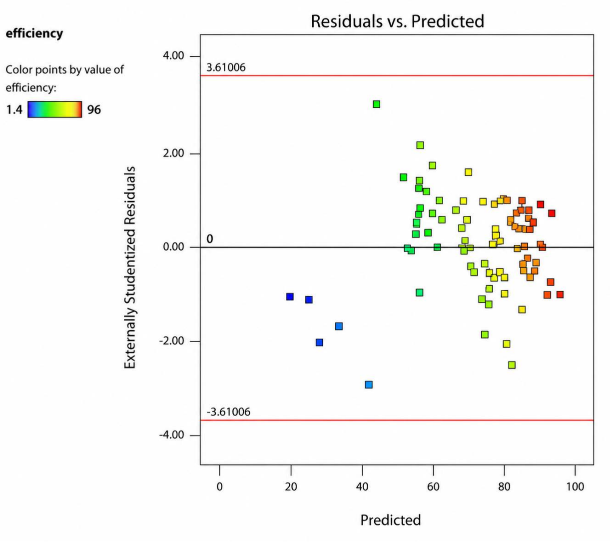

Figure 3. Error Chart against Predicted Values for Efficiency

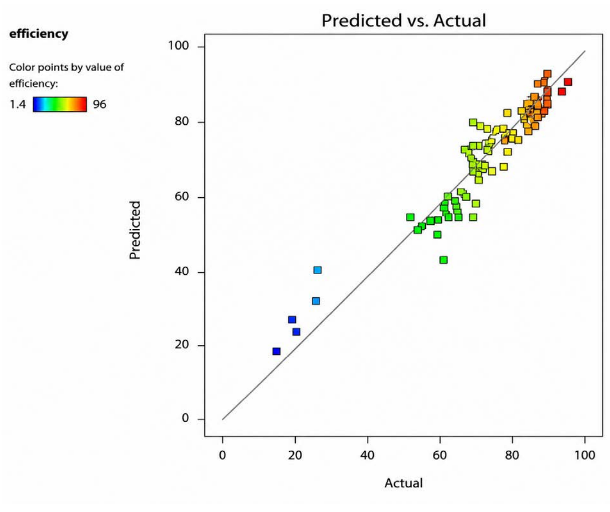

Figure 4. Plot of predicted versus experimental values for efficiency

Table 4. Some of the proposed solutions in the operational parameters' optimization stage Validation Tests

Nozzle type	Liquid flow rate (L/Min)	Gas flow rate (ft³/Min)	Inlet concentration (ppm)	Number of nozzles	Solution number
80ss Berto	6	158	60	3	**1**
30ss Berto	5	132	90	3	2
80ss Berto	6	132	90	2	3
80ss Berto	4	158	120	3	4
80ss Berto	5	132	90	2	5
30ss Berto	5	158	90	3	6
30ss Berto	5	132	120	2	7
30ss Berto	6	158	60	3	8

lower weights set to 1.

Confirmation experiments were then conducted under the optimized conditions predicted by the software to verify the accuracy and reliability of the optimization results. The validation of the regression equations and the solutions proposed by the software was carried out by selecting and performing eight randomly chosen experiments from the suggested list. Each of these eight experiments was repeated three times, and the mean results are presented in the column of observed values.

The eight experiments reported in Table 4 yielded the following predicted values for the response variable, namely SO_2 removal efficiency: 89, 82, 88, 80, 85, 81, 73, and 84. Correspondingly, the observed removal efficiencies were obtained as 80, 75, 81, 74, 80, 65, 60, and 71, respectively.

Table 5 shows the percentage differences between the predicted values and the experimental observations. All values in this table are rounded.

Effect of Operating Parameters on Gas Removal Efficiency from the Spray Tower

ANOVA analysis revealed that the factors A, B, C, D, E, CD, CE, and DE are significant indicators of removal efficiency. Among these, the nozzle type emerged as the most important variable, evidenced by the highest F-value of 188.87. The number of nozzles is the second most important variable. Figure 5 illustrates the combined effect of liquid volume flow and inlet gas concentration. The maximum removal efficiency of 81.5% is achieved at a concentration of 60 ppm and a liquid volume flow of 6 L/min. Increasing the liquid volume flow resulted in a significant increase in the removal efficiency of the spray tower ($P < 0.0001$) (Figure 5).

The figure shows that, in general, the removal efficiency decreases as gas concentration and volumetric flow increase. While the impact of the gas flow volume on removal efficiency is significant, it is relatively weak compared to the effect of gas concentration ($P = 0.0224$). From the figure, it is evident that the highest removal efficiency of 79.7% is achieved at a gas flow volume of 105 CFM and an inlet gas concentration of 60 ppm (Figure S1).

Figure S2 illustrates the combined effect of the inlet gas concentration and the number of nozzles on the removal efficiency, with a gas flow rate of 132 CFM and a liquid flow rate of 5 L/min. The figure shows that the highest removal efficiency of 83% is achieved with 3 nozzles and an inlet gas concentration of 60 ppm. The number of nozzles significantly impacts removal efficiency ($P < 0.0001$). Furthermore, there is a strong interaction between the inlet gas concentration and the number of nozzles ($P < 0.0001$). Increasing the number of nozzles and decreasing the gas concentration entering the spray tower results in higher removal efficiency (Figure S2).

The statistical analysis table revealed that the gas concentration entering the spray tower and the number of nozzles, based on the type of nozzle used, significantly impact removal efficiency ($P < 0.0001$). Figure S3 (a and b) illustrates the effects of the inlet gas concentration and the number of nozzles on efficiency for the three different nozzles. The blue lines represent the 2500-micron nozzle, the red lines represent the Berto ss30 nozzle, and the green lines represent the Berto 80ss nozzle. According to the figure, the Berto ss80 showed better removal efficiency; the Berto ss30 nozzles exhibited higher removal efficiency (Figure S3).

After executing the tests and inputting the results into the software, several optimization tests were recommended by the software. To verify the optimization conditions, the experiments were conducted three times. Upon analysis, it was found that the average difference between the predicted values and the measured values was -12%.

Discussion

The removal of sulfur dioxide (SO_2) from industrial emissions is a critical aspect of air pollution control. This study extensively examined the effect of operational parameters in a spray tower scrubber to enhance the efficiency of SO_2 removal. The findings underscore the

Table 5. Comparison of predicted and observed values

	Test No.	Result	Test No.	Result
Predicted Efficiency (%)	1	89	5	85
	2	82	6	81
	3	88	7	73
	4	80	8	84
Observed Efficiency (%)	1	80	5	80
	2	75	6	65
	3	81	7	60
	4	74	8	71
Average percentage difference in efficiency:			-0.12	

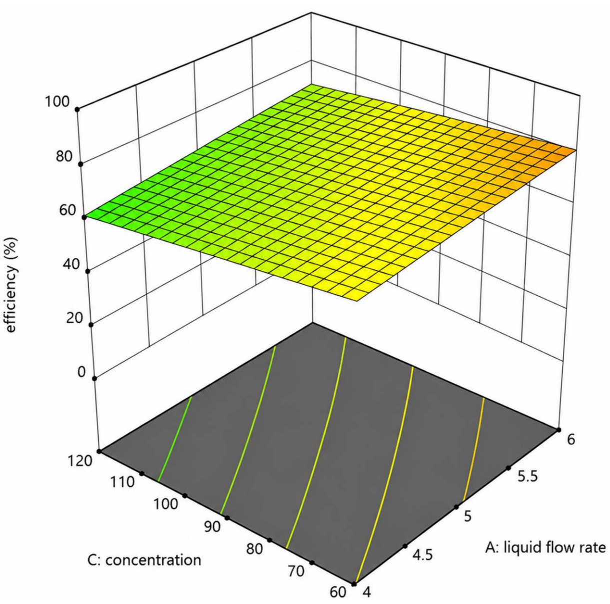

Figure 5. Three-dimensional image of the simultaneous effect of liquid concentration and volumetric flow on

importance of optimizing variables such as liquid flow rate, gas flow rate, inlet gas concentration, nozzle type, and the number of nozzles to achieve maximum efficiency. Below, each factor and its interaction with others are analyzed in detail.

Liquid Flow Rate

Liquid flow rate is one of the most influential parameters in determining removal efficiency. An increase in the liquid flow rate enhances the interaction between the gas and liquid phases by increasing the surface area and the mass transfer driving force. This allows more SO_2 to be absorbed into the liquid droplets, leading to a significant improvement in removal efficiency.

For instance, at a gas flow rate of 105 ft^3/min and a gas concentration of 60 ppm, increasing the liquid flow rate from 4 to 6 L/min raised the efficiency from 78% to 89%. This trend is consistent across other operational setups and aligns with the findings of Liu et al. (2020), who demonstrated that increased liquid flow creates finer droplets and a more homogeneous distribution, which facilitates enhanced gas-liquid interaction (13).

Gas Flow Rate

Gas flow rate is inversely proportional to the removal efficiency. As the gas flow rate increases, the gas retention time within the scrubber decreases, reducing the contact time between the gas and liquid droplets. Moreover, higher gas velocities can disrupt the spray pattern, leading to a less effective interaction between the phases. In this study, increasing the gas flow rate from 105 to 158 ft^3/min resulted in an increase in removal efficiency from 89% to 83% for the Berto SS80 nozzle under otherwise optimal conditions. These findings are consistent with the findings of the research by Chu et al. (2018), which highlighted that elevated gas flow rates increase turbulence but reduce the efficiency of pollutant removal due to shorter residence times (16).

Inlet Gas Concentration

The concentration of SO_2 entering the scrubber is a critical determinant of removal efficiency. Higher inlet concentrations lead to a reduced liquid-to-gas molar ratio, causing the absorbent to reach saturation more quickly. This limits the capacity of the liquid to absorb additional SO_2, thus decreasing the efficiency. For example, under average liquid and gas flow rates, increasing the inlet gas concentration from 60 ppm to 120 ppm reduced the removal efficiency from 96% to 78% for the Berto SS80 nozzle. This trend was particularly pronounced for the 2500-micron nozzle, which exhibited a significant drop in performance due to its inability to maintain effective contact with the gas at higher concentrations. These results align with the results of studies by Jia et al. (2017) and Rahmati et al. (2018), which found that higher gas concentrations overwhelm the reactive capacity of the absorbent, leading to reduced absorption rates (12,24).

Number of Nozzles

The number of nozzles in the spray tower has a direct and positive impact on the removal efficiency. Increasing the number of nozzles results in a greater number of liquid droplets and a higher overall liquid-to-gas ratio. This not only enhances the likelihood of collision and interaction between gas molecules and liquid droplets but also ensures a more uniform distribution of the liquid phase. For the Berto SS80 nozzle, increasing the number of nozzles from one to three raised the removal efficiency from 68% to 96% under optimal conditions. Similarly, for the 2500-micron nozzle, the efficiency improved from 25% to 68% when the number of nozzles increased from one to three. These findings are consistent with those of Codolo et al. (2013), who demonstrated that increasing nozzle density significantly enhances droplet coverage and interaction potential (11).

Nozzle Type

The type of nozzle may be the most critical factor in determining the overall performance of the spray tower. Among the three nozzle types tested in this study (Berto SS30, Berto SS80, and 2500-micron), the Berto SS80 nozzle consistently exhibited superior performance, achieving up to 96% efficiency. This can be attributed to its ability to produce smaller, more uniform droplets, which facilitate better mass transfer between the gas and liquid phases. In contrast, the 2500-micron nozzle performed poorly due to its larger droplet size, which disrupted the spray pattern and reduced the effective contact time between the gas and liquid. These findings are in line with those of the research by Liu et al. (2020) and Darake et al. (2014), which emphasize the importance of nozzle design in optimizing droplet size and distribution for maximum efficiency (13,15).

Interaction Effects

The interplay between different operational parameters plays a crucial role in optimizing removal efficiency. For instance, the combined effect of inlet gas concentration and the number of nozzles was found to be significant. At a gas flow rate of 132 ft^3/min and a liquid flow rate of 5 L/min, increasing the number of nozzles from one to three mitigated the negative impact of higher inlet concentrations, maintaining efficiency levels above 80%. Similarly, the interaction between liquid flow rate and nozzle type revealed that the SS80 Berto nozzle was particularly effective at higher liquid flow rates, achieving efficiencies above 90% even at elevated gas concentrations. These findings underscore the importance of a holistic approach to parameter optimization, as highlighted in studies by Codolo et al. (2013) and Chu et al. (2018) (11,16).

Practical Implications

The findings of this study have several practical implications for industrial applications. For facilities operating under high gas flow rates or elevated pollutant concentrations, increasing the number of nozzles and optimizing the liquid flow rate can significantly enhance removal efficiency. Additionally, selecting the appropriate nozzle type, such as the Berto SS80, can maximize performance while minimizing operational costs. The use of alternative absorbents, such as alkaline solutions, is also recommended to further improve efficiency and reduce the risk of saturation. Moreover, integrating the spray tower with other scrubbing systems, such as packed bed columns or venturi scrubbers, could provide additional removal capacity while optimizing energy and water usage.

Future Research Directions

While this study provides valuable insights, there are several avenues for future research. Investigating the use of seawater instead of freshwater as an absorbent could reduce operational costs and environmental impact, particularly in coastal regions. Additionally, exploring the application of novel absorbents with higher chemical reactivity and absorption capacities could further enhance performance. Other areas of interest include the development of advanced nozzle designs that optimize droplet size and distribution and the integration of computational fluid dynamics (CFD) simulations to model and predict the performance of spray towers under various operating conditions. These approaches could provide a more comprehensive understanding of the underlying mechanisms and support the development of more efficient and sustainable air pollution control technologies.

Conclusion

This study highlights the critical role of operational parameters in determining the efficiency of SO_2 removal in spray towers. By optimizing factors such as liquid flow rate, gas flow rate, inlet gas concentration, nozzle type, and the number of nozzles, significant improvements in removal efficiency can be achieved. The Berto SS80 nozzle emerged as the most effective option, achieving efficiencies of up to 96% under optimal conditions. Future efforts should focus on the development of advanced scrubber designs and the exploration of alternative absorbents to further enhance efficiency and sustainability. These advancements will be essential in meeting stringent environmental regulations and mitigating the impact of industrial emissions on human health and the environment.

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Competing Interests

The authors declare no conflict of interest.

Ethical Approval

The study was approved by the Research Ethics Committee of Shahid Beheshti University of Medical Sciences, Tehran, Iran. (IR.SBMU.PHNS.REC.1400.069).

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Supplementary Files

Supplementary file 1 contains Figure S1-S3.

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