



# Enhanced Efficiency of the Sieve Tray in a Desulfurization Spray Scrubber

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The wet flue gas desulfurization (WFGD) system is widely used in coal-fired power plants worldwide. Improving its efficiency is very important for economical running. In this study, SO<sub>2</sub> removal by the spray scrubber by adding a new sieve tray was studied and compared to that by the traditional spray scrubber without a sieve tray (the WFGD system). The effects of gas flow rate, liquid flow rate, inlet SO<sub>2</sub> concentration, and pH value on both types of scrubbers were evaluated. Pore diameter and porosity of the sieve tray in the sieve-tray spray scrubber were determined, and its enhanced efficiency under different experimental conditions was calculated. The results showed that the enhanced efficiency increased with the increasing liquid flow rate, gas flow rate under the same liquid/gas ratio (L/G), and pH value. Compared to the spray scrubber without a sieve tray, the sieve-tray spray scrubber had significantly higher efficiency. The enhanced efficiencies were mostly between 20% and 60% in the experimental range.

**Keywords:** wet flue gas desulfurization, spray scrubber, SO<sub>2</sub> removal, sieve tray, enhanced efficiency

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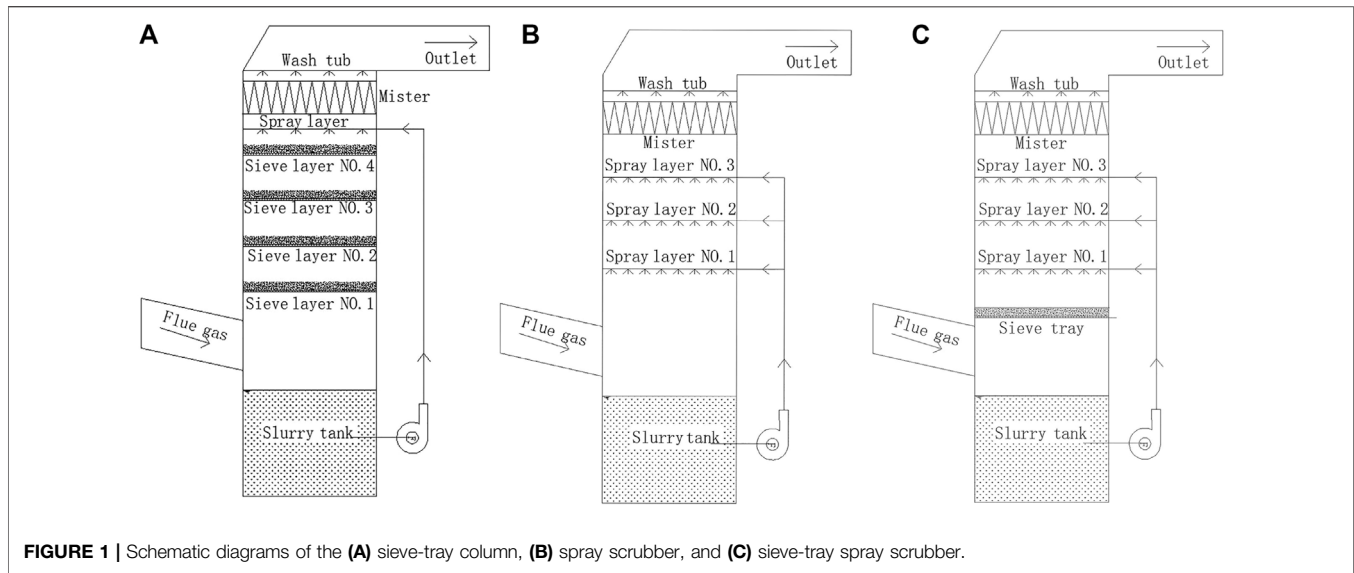
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## 1 INTRODUCTION

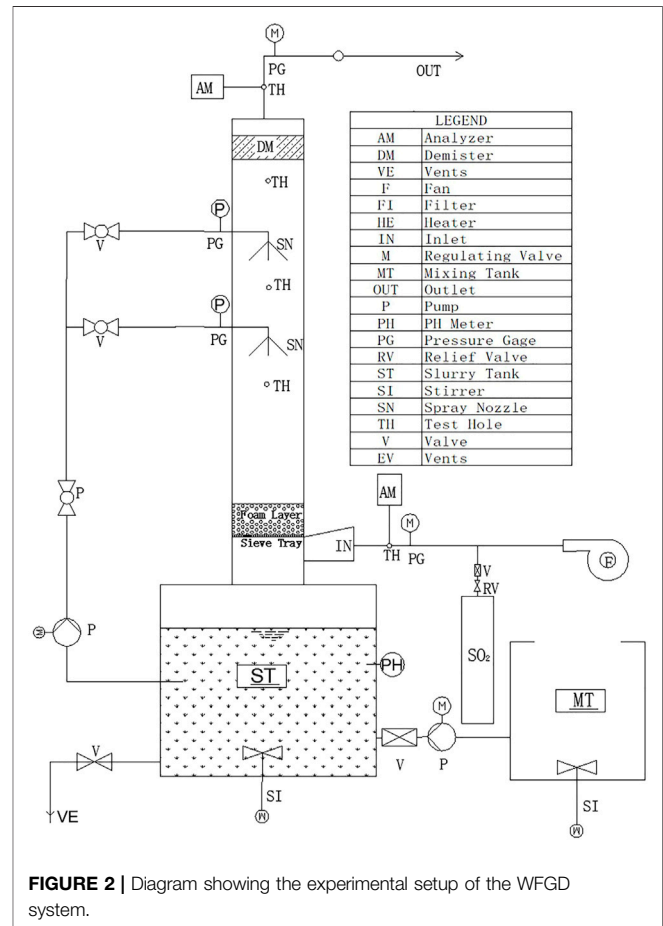
Sulfur dioxide (SO<sub>2</sub>) is one of the major air pollutants which can cause great damage to human health and environmental sustainability (Braghiroli et al., 2019). SO<sub>2</sub> is mostly produced by industrial activities, especially in the process of burning fossil fuels in the power plants. More and more policies have been announced on reducing SO<sub>2</sub> emissions in many countries; furthermore, the pollutant emission standards have become increasingly strict over the past 10 years (Zhu et al., 2015; Liu et al., 2016a). For instance, a new environmental protection policy called the ultra-low emission regulation was announced in China, which sets the limit of SO<sub>2</sub> emission from all coal-fired boilers with a generation capacity of more than 300 MW to 35 mg/m<sup>3</sup>, which is stricter than the limits set by other countries (about 200 mg/m<sup>3</sup>) (Moullec, 2011; Kermani, 2018). It is a challenge to accomplish the ultra-low emission requirement of 35 mg/m<sup>3</sup> for SO<sub>2</sub> while it caused more energy consumption.

Due to the high SO<sub>2</sub> removal efficiency and reliability and low energy consumption (Liu et al., 2016b), wet flue gas desulfurization (WFGD) using lime or limestone slurry is widely employed in coal-fired power plants and other industries. For meeting the increasingly stringent environmental requirements and improving the cleanliness of coal utilization, many methods have been developed to improve the SO<sub>2</sub> removal efficiency. Adding more spray layers to improve the liquid-gas ratio or a new WFGD tower for forward removal of SO<sub>2</sub> is a common method, while these methods require additional energy input and expensive investment costs (Tong et al., 2019). A different method is to use a new technology or innovative materials (Pedrolo et al., 2017; Gao and He, 2018), such as a high-gravity rotating packed bed (Chen et al., 2020) or alkaline solvents in a membrane contactor (Zhao and Liang, 2014). However, the SO<sub>2</sub> removal process or sorbents used in these methods need to be changed, which is highly costly since 90% of the existing SO<sub>2</sub> removal systems worldwide use the



WFGD system (Moullec, 2011). In order to lower the investment cost for ultra-low emission requirements, some improvement methods have been studied, such as optimizing the layout of the spray layer and sprayers' distribution (Zhao and Liang, 2014), rectifying nozzles (Schick, 2014), adding an internal rod bank (Dai, 2017) or a sieve tray to the spray scrubber (Wu et al., 2019a). Among these strategies, using a sieve tray which requires only minor modifications of the existing WFGD system of power plants is considered the most promising strategy that can improve the removal of  $\text{SO}_2$  and other pollutants.

Sieve trays widely used in distillation are generally divided into two groups: 1) sieve tray with downcomers and 2) sieve tray without downcomers. The sieve tray with downcomers has an effective area of 60–70% of the column cross-sectional area (Ludwig, 1997). A sieve tray without a downcomer has a larger bubbling/effective area, so it can increase 20%–30% capacity and lower the pressure drop, but has lower efficiency than a sieve tray with downcomers (Gondosurohardjo et al., 2019). Sieve trays without downcomers are known to cause the countercurrent flow of liquid and vapor. Thus, they are also often called sieve trays with the dual flow or dual-flow sieve trays and are widely used in the chemical industry (Flávio et al., 2014). Although the sieve-tray column with several sieve trays (Figure 1A) has high efficiency for mass transfer, it cannot be used in power plants to enhance the  $\text{SO}_2$  removal because a mixture of  $\text{CaCO}_3$ ,  $\text{CaSO}_4$ , and  $\text{CaSO}_3$  is generated in the WFGD system, and the flue gas contains a large number of dust particles that can easily lead to column blockage (Wu et al., 2019b). In the traditional WFGD spray scrubber (Figure 1B), the non-uniform distribution of the gas and liquid can decrease the mass transfer efficiency (Liu et al., 2016b). Thus, a new sieve-tray spray scrubber (Figure 1C), which contains both the spray layers and the sieve tray, should help improve the  $\text{SO}_2$  removal efficiency and reduce the risk of blockage. In the new spray scrubber, the original spray layers are retained, and only a sieve tray is reinstalled. Compared with the method of adding a nozzle



or rectifying a spray layer, it can greatly eliminate the investment cost and enhance efficiency.

In the sieve-tray spray scrubber, one sieve tray is installed under the spray layers to regularize the gas flow and generate a

foam layer on the sieve tray. The gas and slurry on the sieve tray can interact with each other, in addition to the strong washing effect of the spray layer. As a result, the sieve tray cannot be easily blocked. Some industrial applications have indicated that the WFGD system with a sieve tray has higher SO<sub>2</sub> removal efficiency than that without a sieve tray (Wu et al., 2019a; Gondosurohardjo et al., 2019; Junhua, 2019). However, most of these applications are based on an overall observation; the precise effect of the sieve tray on the SO<sub>2</sub> removal has not been observed. For this reason, the effect of the sieve trays on the enhanced SO<sub>2</sub> removal efficiency remains unclear.

Therefore, this study comprehensively analyzed the factors affecting the SO<sub>2</sub> removal efficiency of the spray scrubber and the sieve-tray spray scrubber, including the gas flow rate, slurry flow rate, pH value, SO<sub>2</sub> concentration, and pore diameter and porosity of sieve trays. The enhanced efficiency of the sieve tray was then evaluated based on these experimental data.

## 2 EXPERIMENT APPARATUS AND MATERIALS

**Figure 2** presents the experimental setup of the WFGD system. The spray scrubber is a vertical transparent perspex column with a length of 2.0 m and an inner diameter of 0.15 m. There are two spray layers (SN) and a mist eliminator (DM) on the top of the column. In sieve-tray spray scrubber experiments, a sieve tray was installed at the bottom of the spray nozzles.

The simulated flue gas was a mixture of air and SO<sub>2</sub> from a gas cylinder (SO<sub>2</sub> > 99%) and was pumped into the scrubber with a fan (V). After SO<sub>2</sub> in the flue gas reacted with the slurry of lime or limestone, which was sprayed from the spray nozzles, the clean gas was exhausted from the scrubber outlet (OUT). The desulfurizing reactant was used with a lime solution and was dissolved in the mixing tank (MT) with CaO powder (99.9%, Wuxi Pridechem Co., Ltd.). The lime solution was pumped into the slurry tank by a peristaltic pump (Kamoer Co., Ltd.). The pumping volume of the peristaltic pump was automatically controlled by the fixed pH value of the slurry tank. A slurry tank with a capacity of 0.064 m<sup>3</sup> was used as a slurry reservoir from which the slurry was pumped out (P). The slurry flow rate was controlled by two valves (V) and was monitored by two in-line flow meters. The concentration of the lime/gypsum slurry was kept constant at 15% by a valve (V) and vents (VE) at the bottom of the slurry tank (ST). The gas temperature of the outlet was maintained at a constant value of 40°C. SO<sub>2</sub> was sampled from the test holes (TH) at the inlet and outlet simultaneously, where its concentration was measured by using two flue gas analyzers (Testo 350).

## 3 RESULTS AND DISCUSSION

SO<sub>2</sub> removal efficiency could be affected by many factors, such as the slurry pH value, droplet diameter, gas flow rate, slurry flow rate, slurry composition, temperature, inlet SO<sub>2</sub> concentration, and structural parameters of the scrubber (Li, 2009; Wu et al.,

2019b). Most of the operational parameters are now fixed for an applied WFGD system. Considering the real running conditions in the industrial application (Lin, 2006), the gas flow rate, slurry flow rate, pH value, and SO<sub>2</sub> concentration were investigated herein because they are the normal adjustable parameters in the real running. In this article, the SO<sub>2</sub> removal efficiency of the spray scrubber with and without a sieve tray was compared based on these four parameters.

The SO<sub>2</sub> removal efficiency was calculated by the following equation (Yi et al., 2018):

$$\eta_{\text{SO}_2} = \frac{C_{\text{SO}_2} - C'_{\text{SO}_2}}{C_{\text{SO}_2}} \times 100\%, \quad (1)$$

where  $\eta_{\text{SO}_2}$  is the SO<sub>2</sub> removal efficiency of the spray scrubber (%),  $C_{\text{SO}_2}$  is the inlet SO<sub>2</sub> concentration (mg/m<sup>3</sup>), and  $C'_{\text{SO}_2}$  is the outlet SO<sub>2</sub> concentration (mg/m<sup>3</sup>).

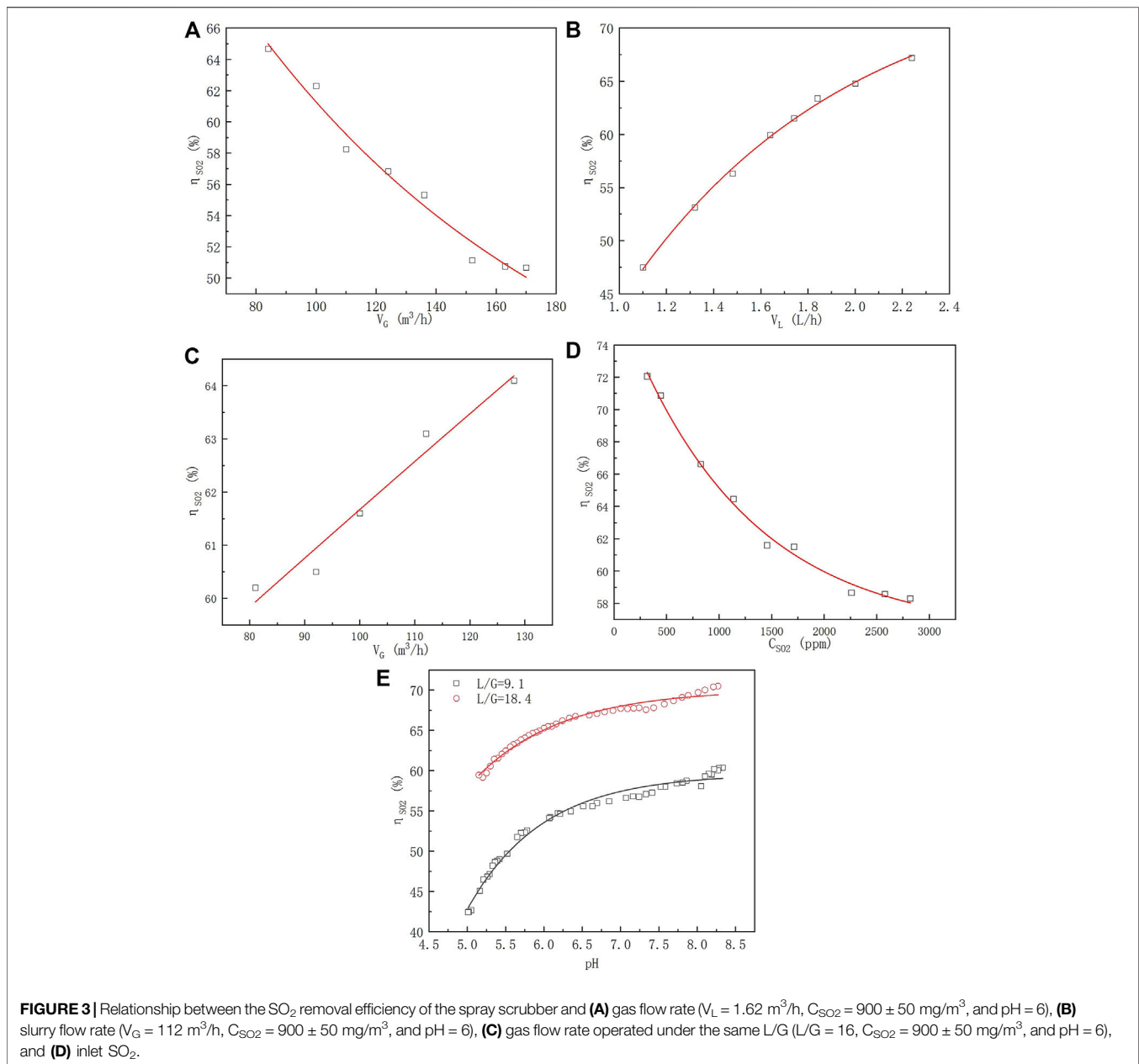
### 3.1 Total Sulfur Dioxide Removal Efficiency of the Spray Scrubber Without a Sieve Tray

The effects of the gas flow rate ( $V_G$ ), slurry flow rate ( $V_L$ ), gas flow rate under the same L/G, SO<sub>2</sub> concentration ( $C_{\text{SO}_2}$ ), and pH value (pH) on the SO<sub>2</sub> removal efficiency ( $\eta_{\text{SO}_2}$ ) of a spray scrubber without a sieve tray are shown in **Figures 3A–E**.

According to **Figure 3A**, the SO<sub>2</sub> removal efficiency declined with the increasing gas flow rate because the residence time of the gas flow significantly decreased over the experimental  $V_G$  range (Lin, 2006). As shown in **Figure 3B**, the SO<sub>2</sub> removal efficiency improved with the raising slurry flow rate from 1.1 L/h to 2.3 L/h. This is likely because the number of droplets rises with the increasing slurry flow rate, and the gas-liquid contact areas become larger. Similar change trends of  $\eta_{\text{SO}_2}$  with  $V_G$  and  $V_L$  have also been demonstrated in other studies (Lin, 2006).

In this work, both  $V_G$  and  $V_L$  were simultaneously adjusted under the same L/G. The results depicted in **Figure 3C** showed that under the same L/G,  $\eta_{\text{SO}_2}$  improved from about 60% to 64% as the gas flow rate increased from 82 to 128 m<sup>3</sup>/h, which is in contrast to the results shown in **Figure 3A** (where  $V_L$  was kept constant). Many studies on the SO<sub>2</sub> removal efficiency have examined the impact of L/G by adjusting either the gas flow rate or liquid flow rate, without considering the simultaneous adjustment of both parameters. For example, Gerbec et al. (1995) fixed the liquid flow rate and varied the gas flow rate to adjust the L/G, while Zhao (2008) fixed the gas flow rate and the liquid flow rate to change the L/G. However, it is not appropriate to adjust the gas flow or liquid flow individually. In actual engineering operations, these two parameters must be adjusted at the same time to reach the emission standard. The different result is that increasing the liquid flow rate can augment the gas-liquid contact area, providing more reactants for the reaction. This finding is of great significance for the practical engineering operations ignored in previous studies (Gerbec et al., 1995).

The relationship between the inlet SO<sub>2</sub> concentration and SO<sub>2</sub> removal efficiency is shown in **Figure 3D**. The SO<sub>2</sub> removal efficiency was sharply reduced from 72.1% to 58.3% when the

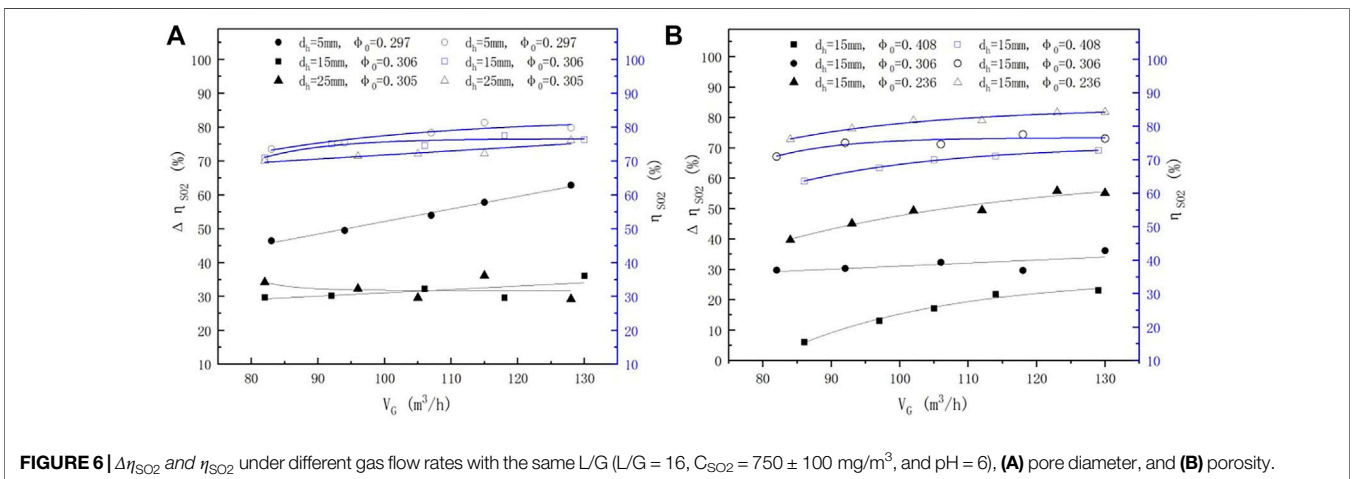
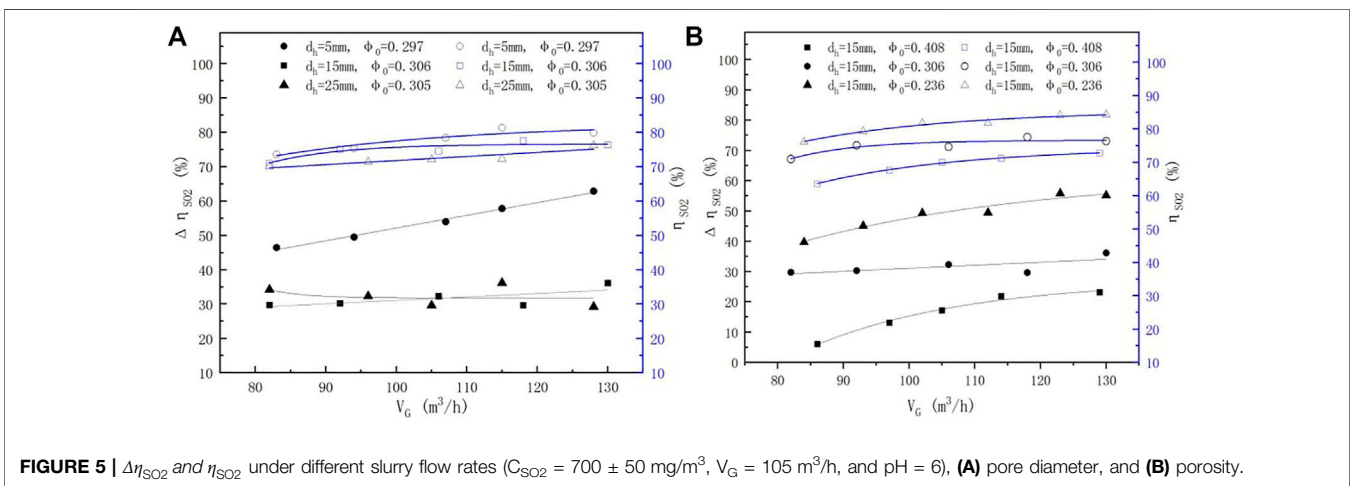
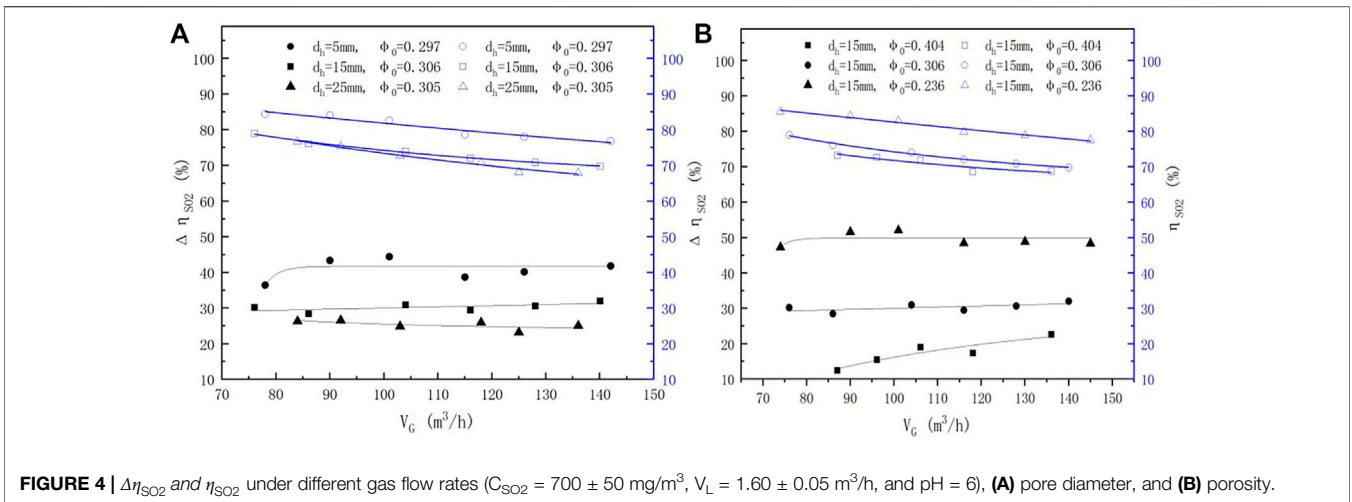


$C_{\text{SO}_2}$  concentration was increased from 315 to 2818 ppm. This may be because the high SO<sub>2</sub> concentration required high consumption of  $\text{Ca}^{2+}$  in the slurry, which caused additional absorption resistance (Lin, 2006).

**Figure 3E** illustrates the change in the SO<sub>2</sub> removal efficiency with different pH values under L/G of 9.1 and 18.4. The  $\eta_{\text{SO}_2}$  values at L/G = 18.4 were higher than those at L/G = 9.1. However, the change in  $\eta_{\text{SO}_2}$  values with pH under different L/G was highly similar. When pH values changed from 5.0 to 6.0, the efficiency was rapidly promoted. Lower pH accelerating the dissolution of lime may be attributed to this result. After that, at pH values higher than 6.0, the efficiency increased more slowly because of the slow dissolution of lime at these pH values. Interestingly, when the pH values rose above 7.5, the

efficiencies were further improved since the higher pH led to the increased amount of alkali in the slurry, which in turn provided more reactants for the reaction (Li, 2009). Although a high pH value can strengthen the SO<sub>2</sub> absorption, it causes calcium sulfite to easily become crystallized on the absorbent surface, preventing it from further absorption and reaction, which also causes the lime dissolution rate to decrease (Zhu et al., 2015). As a result, pH values should be controlled between 5.0 and 6.0 in the industrial operation process.

In short, the gas flow rate, slurry flow rate, pH value, and SO<sub>2</sub> concentration are the four parameters that are promising for SO<sub>2</sub> removal efficiency. Although changing the aforementioned parameters can improve the removal efficiency of SO<sub>2</sub>, it is hard to adjust the SO<sub>2</sub> concentration in real operation, for it is





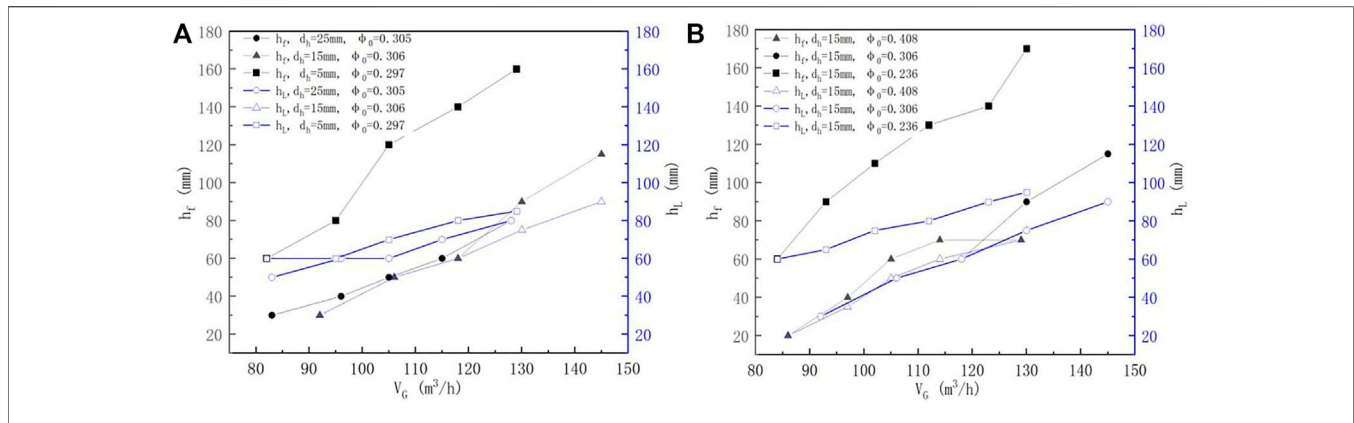


FIGURE 7 | Variation of the foam height ( $h_f$ ) and clear liquid height ( $h_l$ ) with different gas flow rates ( $L/G = 16$ ), (A) pore diameter, and (B) porosity.

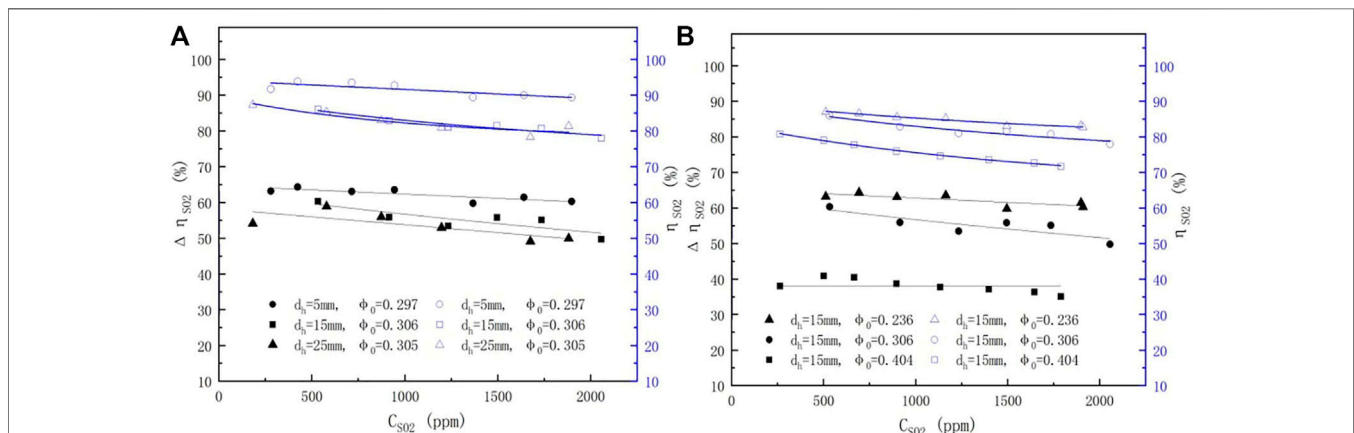


FIGURE 8 |  $\Delta \eta_{\text{SO}_2}$  and  $\eta_{\text{SO}_2}$  under different  $\text{SO}_2$  concentrations ( $V_L = 1.60 \text{ m}^3/\text{h}$ ,  $V_G = 95 \text{ m}^3/\text{h}$ , and  $\text{pH} = 6$ ), (A) pore diameter, and (B) porosity.

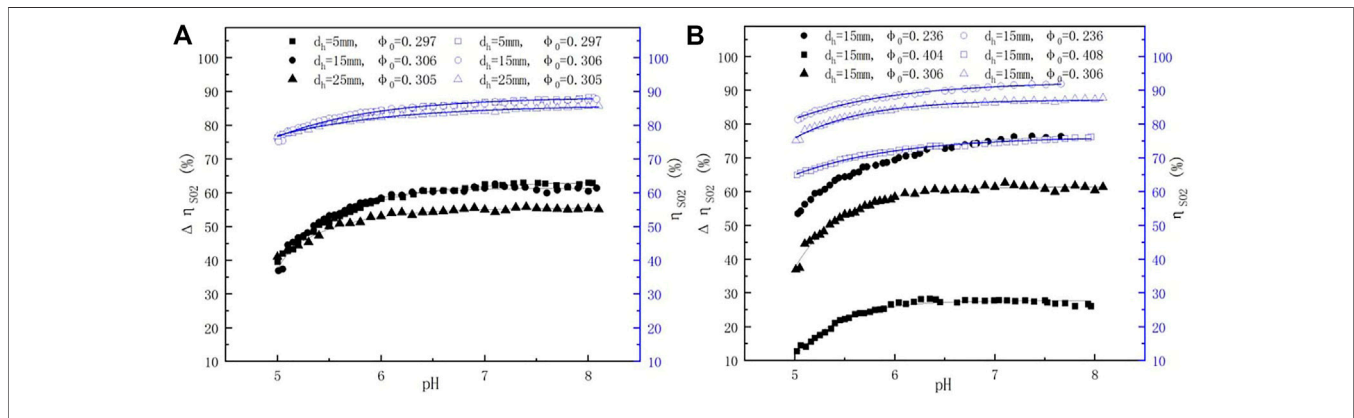


FIGURE 9 |  $\Delta \eta_{\text{SO}_2}$  and  $\eta_{\text{SO}_2}$  under different pH values ( $V_L = 1.6 \text{ m}^3/\text{h}$ ,  $V_G = 95 \text{ m}^3/\text{h}$ , and  $C_{\text{SO}_2} = 750 \pm 100 \text{ mg}/\text{m}^3$ ), (A) pore diameter, and (B) porosity.

determined by the coal quality in the combustion. Owing to the reaction principle, the liquid flow rate is controlled by the slurry pump, and the pH value is also not easy to adjust. Furthermore, such methods as reducing the gas flow rate or increasing the

slurry flow rate consume extra energy, which leads to a higher operating cost for the power plant. Therefore, in this study, the sieve-tray spray scrubber was employed to improve the  $\text{SO}_2$  removal efficiency without adding much energy consumption.

### 3.2 Total Sulfur Dioxide Removal Efficiency of the Sieve-Tray Spray Scrubber

In addition to the parameters discussed earlier (as in the spray scrubber without a sieve tray), one important factor that impacts the efficiency of the sieve-tray spray scrubber is the sieve tray. Also, the pore diameter and porosity are two key parameters of the sieve tray which affect the SO<sub>2</sub> removal efficiency (Chuang, 1993; Xu et al., 1994). The effects of the aforementioned values on the total SO<sub>2</sub> removal efficiency of the sieve-tray spray scrubber are shown in Figures 4–9 (right Y-axis; blue).

#### 3.2.1 Impact of Gas Flow Rates

Figure 4 depicts the total efficiency of the sieve-tray spray scrubber ( $\eta_{\text{SO}_2}$ ) under different gas flow rates. Figure 4A shows the  $\eta_{\text{SO}_2}$  at different pore diameters ( $d_h = 5, 10,$  and  $15$  mm) with a nearly constant porosity ( $\phi_0 \approx 0.3$ ). According to the curve, the  $\eta_{\text{SO}_2}$  values at  $d_h = 5$  mm were much higher than those at other  $d_h$  values because pores with smaller diameters can disperse the continuous flow of gas into smaller bubbles (Im et al., 2018), which can enlarge the contact area of the gas and liquid. Furthermore, the changes in  $\eta_{\text{SO}_2}$  at  $d_h = 15$  and  $25$  mm were not obvious, which illustrates that the bubbles may be too large to impact the mass transfer of the sieve tray. Figure 4B further shows that  $\eta_{\text{SO}_2}$  values when the sieve tray with lower porosity was used were much higher than those when the sieve tray with a larger porosity was used. This is because the turbulence of the gas–liquid interaction in the sieve tray with lower porosity is much higher, which could substantially strengthen the mass transfer between the gas and liquid (Wu et al., 2019b).

#### 3.2.2 Impact of Slurry Flow Rates

Figure 5 shows the relationship between the liquid flow rate and  $\eta_{\text{SO}_2}$ . In Figure 5A, the  $\eta_{\text{SO}_2}$  values at  $d_h = 5$  mm were about 1%–5% higher than those at other diameters, indicating that in the experimental range, the impact of the slurry flow rate on the  $\eta_{\text{SO}_2}$  values is not obvious than that of the gas flow rate. According to Figure 5B, the  $\eta_{\text{SO}_2}$  values increased with increasing  $V_L$  and decreasing porosity, and the same trends were observed in the spray scrubber without a sieve tray. These results indicated that porosity can significantly impact  $\eta_{\text{SO}_2}$ , and a lower porosity can enhance the mass transfer of the foam layer (Chuang, 1993; Xu et al., 1994).

#### 3.2.3 Impact of Gas Flow Rates With the Same L/G

As described earlier, maintaining the L/G at a stable level while simultaneously adjusting  $V_G$  and  $V_L$  can impact the SO<sub>2</sub> removal efficiency. Results under the same L/G but different pore diameters and porosity are illustrated in Figures 6A,B. It can be seen that the  $\eta_{\text{SO}_2}$  values increased when only  $V_G$  was increased, which contradicts the results shown in Figure 3A, where the slurry flow rate remained constant. This is likely because the improvement of the slurry flow rate can increase the reactant supply. As shown in Figure 6B, the  $\eta_{\text{SO}_2}$  values increased about 4% and 10% when the porosity declined from 0.408 to 0.306 and 0.236, respectively. This reveals that lower

porosity can strengthen the mass transfer of the sieve tray, which has been demonstrated by many studies (Chuang, 1993; Xu et al., 1994; Syeda, 2007; Li, 2009; Flávio et al., 2014).

#### 3.2.4 Impact of the Sulfur Dioxide Concentration

The impact of the SO<sub>2</sub> concentration on the SO<sub>2</sub> removal efficiency at constant  $V_L$ ,  $V_G$ , and pH but different pore diameters and porosity is shown in Figure 7. According to Figures 7A,B, the increase in  $C_{\text{SO}_2}$  lowered  $\eta_{\text{SO}_2}$ , which may be due to the fact that the SO<sub>2</sub> concentration is proportional to the partial pressure of SO<sub>2</sub> in the flue gas (Lin, 2006). Raising the SO<sub>2</sub> concentration can elevate the SO<sub>2</sub> absorption rate in the gas–liquid reaction. However, since the elevation in the absorption rate is less than that of the SO<sub>2</sub> concentration, the total mass transfer of SO<sub>2</sub> is reduced with the increase in the inlet SO<sub>2</sub> concentration (Chen, 2008). Moreover, it can also be seen that the smaller pore diameter and porosity can enhance the SO<sub>2</sub> removal efficiency, as described earlier.

#### 3.2.5 Impact of pH Values

The correlation between pH values and SO<sub>2</sub> removal efficiency at different pore diameters and porosity is shown in Figure 8. The  $\eta_{\text{SO}_2}$  values increased with increasing pH values and became stable at high pH values. In addition, the  $\eta_{\text{SO}_2}$  values at  $d_h = 5$  mm and  $15$  mm were slightly higher than those at  $d_h = 25$  mm, and the  $\eta_{\text{SO}_2}$  values also improved by nearly 5%, 15%, and 20% in relation to those of the spray scrubber without a sieve tray when  $\phi_0$  was decreased from 0.408, 0.306, and 0.236, respectively. These results indicated that to improve the SO<sub>2</sub> removal efficiency, it is better to adjust the porosity rather than the pore diameter at the experimental range.

### 3.3 Enhanced Efficiency of the Sieve Tray

Consequently, the sieve-tray spray scrubber had a higher SO<sub>2</sub> removal efficiency than the traditional spray scrubber according to the aforementioned data. For further discussion, defining and calculating the “enhanced efficiency” to explore the effect of sieve trays in the sieve-tray spray scrubber is necessary.

#### 3.3.1 Calculation of the Enhanced Efficiency of Sieve Trays

Unlike the traditional distillation tower or multistage dual-flow sieve plate column using sieve trays, the efficiency of the sieve-tray spray scrubber relies on two important parameters: the spray layer and the sieve tray (Flávio et al., 2014). In this study, the spray layer and the sieve tray were assumed to be connected in parallel (Wu et al., 2019a). In other words, the total efficiency of the sieve-tray spray scrubber is the combination of individual efficiencies of the spray layer and the foam layer. Consequently, the enhanced efficiency of the sieve tray ( $\Delta\eta_{\text{SO}_2}$ ) can be calculated from the total efficiencies of the spray scrubber ( $\eta'_{\text{SO}_2}$ ) and the total efficiencies of the sieve-tray spray scrubber ( $\eta_{\text{SO}_2}$ ), which can be calculated as follows:

$$\eta'_{\text{SO}_2} = 1 - (1 - \Delta\eta_{\text{SO}_2})(1 - \eta_{\text{SO}_2}). \quad (2)$$

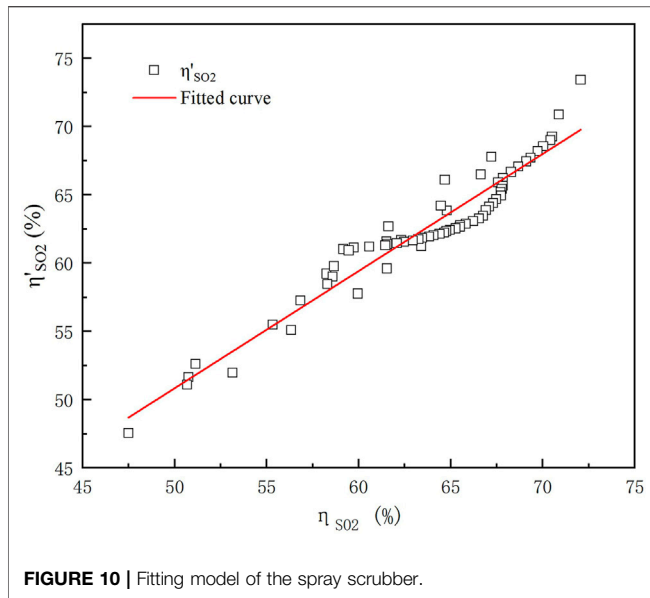


FIGURE 10 | Fitting model of the spray scrubber.

Rearranging **Equation 2**, the equation for calculating the enhanced efficiency of the sieve tray in the sieve-tray spray scrubber can be obtained:

$$\Delta\eta_{SO_2} = 1 - \frac{1 - \eta'_{SO_2}}{1 - \eta_{SO_2}} \quad (3)$$

The results are most accurate when the experimental conditions for both the spray scrubber and the sieve-tray spray scrubber are kept consistent. However, such consistency is difficult to achieve (Chuanbo et al., 2019) because it is not easy to keep all the experimental conditions always the same, which could cause problems when calculating the exact  $\Delta\eta_{SO_2}$ . Therefore, to reduce deviation in the calculation of  $\Delta\eta_{SO_2}$ , a fitting model for the spray scrubber was built based on the experimental data from the spray scrubber by Origin software, and the fitting model is shown in **Equation 4**. From the model, it can be seen that the index value of  $V_L$  is higher than that of  $V_G$ , which is different from most previously reported models regarding  $L/G$ . The different index values of  $V_L$  and  $V_G$  can resolve the problem that the efficiency is hard to be reflected under the same  $L/G$ . Correlation analysis of the desulfurization efficiency showed that the R value of the model was 0.93, and a good agreement between the calculated efficiency and the experimental efficiency was obtained, as shown in **Figure 10**.

$$\eta'_{SO_2} = \frac{526.589 \times V_L^{0.4968} \times C_{SO_2}^{0.104}}{V_G^{0.3735} \times \ln(10^{(14-pH)} + 0.7943)} \quad (4)$$

Before determining the enhanced efficiency of the sieve tray, the  $SO_2$  removal efficiency of the spray scrubber was calculated using the same experimental conditions used for the sieve-tray spray scrubber. Compared to the theoretical models (Li, 2009; Marocco, 2010), the enhanced efficiency of the sieve tray was calculated based on the aforementioned model to become much more precise. The method to resolve the problem of the enhanced efficiency of the sieve tray has seldom been reported (Chen, 2008; Aldo and Lau, 2014; Sadegh and Najafi, 2019).

### 3.3.2 Enhanced Efficiency of the Sieve Tray

The enhanced efficiency of the sieve tray ( $\Delta\eta_{SO_2}$ ) under different key factors was determined, as shown in **Figures 4–9** (left Y-axis; black).

#### 3.3.2.1 Impact of Gas Flow Rates

**Figure 4** shows the results of  $\Delta\eta_{SO_2}$  under different gas flow rates.  $\Delta\eta_{SO_2}$  increased with decreasing pore diameter, and the increment at smaller pore diameters was more obvious than that at larger pore diameters (**Figure 4A**). The average  $\Delta\eta_{SO_2}$  was promoted from 17.2% to 49.4% when the porosity decreased from 0.404 to 0.236 (**Figure 4B**), which is consistent with the observations of distillation towers reported by XU (Xu et al., 1994). Another discovery was that  $\Delta\eta_{SO_2}$  remained stable at different gas flow rates, which is different from the total  $SO_2$  removal efficiency for the spray scrubber or the sieve-tray spray scrubber under different gas flow rates observed in this study. The combined effect of the gas–liquid turbulence intensity and the cut down of the gas–liquid contact time may contribute to this result (Garcia and Fair, 2002). These results indicated that pore diameter and porosity are highly important parameters affecting  $\Delta\eta_{SO_2}$  (Xu et al., 1994). Under the same pore diameter or porosity, the gas flow rates have little impact on  $\Delta\eta_{SO_2}$ . Thus, in order to remove more  $SO_2$  in actual industrial operations, it is better to adjust the pore diameter or porosity rather than to lower the gas flow rate.

#### 3.3.2.2 Impact of Slurry Flow Rates

The influence of the slurry flow rate on the enhanced efficiency at different pore diameters is shown in **Figure 5A**. The enhanced efficiency increased with the decreasing pore diameter of the sieve tray at a constant  $\phi_0$  of  $0.3 \pm 0.01$ , which is likely because smaller pore diameters can better disperse the gas flow into many small bubbles (Xu et al., 1994; Meng et al., 2019), and increase the contact area between the gas and liquid. The impact of porosity on the enhanced efficiency is shown in **Figure 5B**. Despite the fact that the sieve tray can improve the uniformity of the flow field in the scrubber (Wu et al., 2019a), the enhanced efficiency was not obvious at a large porosity of 0.404, for the foam layer was not properly formed. Nonetheless, the enhanced efficiency remained as high as 10–20% with nearly no froth height formatted, which may be due to the effect of the improvement of the flow field. Moreover, with decreasing porosity, the enhanced efficiency increased rapidly, likely due to the fact that the foam layer was improved. These results illustrated that the enhanced efficiency of the sieve tray is significant at smaller pore diameter and porosity, especially under a larger slurry flow rate.

#### 3.3.2.3 Impact of Gas Flow Rates With the Same L/G

The enhanced efficiency of the sieve tray under the same  $L/G$  was calculated, and the results are shown in **Figure 6**. As illustrated in **Figure 6A**,  $\Delta\eta_{SO_2}$  increased with increasing  $V_G$  at  $d_h = 5$  mm and  $L/G = 16$ , but the increment was not apparent at larger  $d_h$ . Moreover, because of the effect of the foam layer, the enhanced efficiency of the sieve tray improved from 29.2% to 34.2%. As depicted in **Figure 6B**, the enhanced efficiency with different porosities is similar to that with other factors. To distinguish



between the enhanced efficiency and the foam layer, the influence of the foam height ( $h_f$ ) and clear liquid height ( $h_L$ ) on the enhanced efficiency was determined (Rahbar, 2012). As shown in **Figures 7A,B**, with an increase in  $h_f$  under different  $V_G$  and same  $L/G$ ,  $\Delta\eta_{SO_2}$  increased significantly only when  $d_h = 5$  mm or  $\phi_0 = 0.236$ . Moreover, the increment was not obvious at larger pore diameters or larger porosity. It is worth noting that at  $d_h = 5$  mm,  $h_f$  was increased from 60 to 160 mm, and  $V_G$  was increased from 82 to 129 m<sup>3</sup>/h, while at  $d_h = 15$  mm and 25 mm,  $h_f$  was only increased from 30 to 80 mm. Additionally,  $h_L$  was improved from about 60 to 80 mm, 30–60 mm, and 50–75 mm when  $d_h$  was 5, 15, and 25 mm, respectively. Obviously,  $h_L$  did not rise with the increase in  $h_f$ . Also, the difference in  $\Delta\eta_{SO_2}$  may be the reason that  $h_L$  did not increase with the increase in  $h_f$ .

The foam porosity (which equals  $1-h_L/h_f$ ) (Xu et al., 1994) is often used to express the relationship between  $h_L$  and  $h_f$ . The results imply that both the foam height and the foam porosity (or the clear liquid height) contribute to the enhanced efficiency because the foam porosity is a physical property involving the mass transfer of a mixture of gas and liquid (Xu et al., 1994). The foam porosity increased rapidly at  $h_f > 80$  mm and  $d_h = 5$  mm, while it was nearly 0 at  $d_h = 15$  and 25 mm. This is the reason that the enhanced efficiency was not apparent at  $d_h = 15$  and 25 mm; the same observations can also be found in **Figure 7B** at  $\phi_0 = 0.306$  and 0.408. Nonetheless, under the same  $L/G$ , the enhanced efficiency increased with the increasing gas flow rate, and the increment was more obvious than that of the spray scrubber without a sieve tray.

To summarize, the enhanced efficiency can be determined, owing to the following three aspects: 1) the sieve tray provided a dense region of the liquid phase, which in turn increased the probability of the contact between  $SO_2$  and the liquid phase in the flue gas; 2) with the decrease in the pore size and porosity, the gas holdup of the foam layer increased, forming a strong vibration of the foam layer. This in turn caused the transfer resistance to reduce and the desulfurization efficiency to increase (Ali and Rahimi, 2013); and 3) due to the effect of the sieve trays, the gas flow field and the liquid distribution field in the tower were improved, resulting in improved gas-liquid distribution and, ultimately, the improved  $SO_2$  removal efficiency (Wu et al., 2019a; Xin et al., 2020).

In addition, it was observed that the pressure drop of the scrubber increased with increasing foam height ( $h_f$ ) and clear liquid height ( $h_L$ ). In this study, the pressure drops observed in different experiments were about 50–500 Pa. Many studies have reported the model for calculating the pressure drop (Chuang, 1993; Xu et al., 1994). Accordingly, for industrial applications, it is better to evaluate the enhanced efficiency by considering the pressure drop.

### 3.3.2.4 Impact of the Sulfur Dioxide Concentration

Enhanced efficiency results under different  $SO_2$  concentrations, pore diameters, and porosities are shown in **Figures 8A,B**. The operating conditions, as well as the status of gas-liquid, were not changed.  $\Delta\eta_{SO_2}$  decreased with the increase in the  $SO_2$  concentration. The probable reason for this result is that high  $SO_2$  concentration makes great consumption of alkali, which in turn decreases the pH values of the slurry, especially for the pH value of the foam layer where the final step of the gas-liquid

reaction took place. As a result, the  $SO_2$  removal efficiency of the foam layer was suppressed (Xu et al., 1994; Chen, 2008). In addition, the enhanced efficiency improved with the reducing pore diameter and porosity, similar to other factors.

### 3.3.2.5 Impact of pH Values

Changes in the enhanced efficiency at different pH values are shown in **Figure 9**. Similar results were obtained from the spray scrubber and the sieve-tray spray scrubber. As shown in **Figure 9A**, at a pH value of less than 6.0,  $\Delta\eta_{SO_2}$  increased rapidly with increasing pH and became stable at a pH value above 6.0. Since the operating conditions were not adjusted, the variation may also be related to the pH values of the foam layer. As illustrated in **Figure 9B**, at  $\phi_0 = 0.404$ ,  $\Delta\eta_{SO_2}$  raised from 3% to 25% when the pH value ranged from 5.0 to 8.0, whereas at  $\phi_0 = 0.236$ ,  $\Delta\eta_{SO_2}$  raised from 53% to 76% under the same pH range. Considering that other factors were not changed in the experiment, the key factor could contribute to the change in properties of the foam layer. In practical applications, the pH value is usually controlled at a lower level to eliminate the risks of blockage, which means that the enhanced efficiency would be less at a lower pH value below 6.0.

## 4 CONCLUSION

Due to the sieve tray's simple structure and easy installation, using it to enhance the  $SO_2$  removal efficiency of the spray scrubber is a convenient and economical way to improve the pollutant removal capacity of the WFGD system. In this article, a new spray scrubber with sieve-tray spray was presented, which made a significant improvement in the total  $SO_2$  removal efficiency compared with the traditional spray scrubber. The total efficiency of the sieve-tray spray scrubber was assumed to be a sum of the individual efficiencies of the spray layer and the foam layer, which were connected in parallel. For further discussion, a fitting model built based on the experimental data for calculating the enhanced efficiency of the sieve-tray spray scrubber was proposed; the enhanced efficiency of the sieve tray in the sieve-tray spray scrubber was calculated and analyzed. The following conclusions were obtained:

- 1) The total  $SO_2$  removal efficiency improved with the increase in the liquid flow rate and gas flow rate under the same  $L/G$ , as well as the increase in the pH value, while it decreased with the increase in the gas flow rate and inlet  $SO_2$  concentration. The  $SO_2$  removal efficiency with different factors of the sieve-tray spray scrubber was similar to that of the spray scrubber without a sieve tray. The  $SO_2$  removal efficiency of different pore diameters and porosities got an absolute value about 1%–31% higher than without it, and with the increasing pore diameter and porosity, the  $SO_2$  removal efficiency decreased.
- 2) The enhanced efficiency increased with the increasing liquid flow rate, gas flow rate under the same  $L/G$ , and the pH value but decreased with the increasing inlet concentration. Meanwhile, under the same pore diameter or porosity, improving only the gas flow rates has little impact on the enhanced efficiency.

- 3) SO<sub>2</sub> removal efficiency of the sieve-tray spray scrubber was considered to be affected by both the spray layer and the foam layer. Compared to the spray scrubber without a sieve tray, the enhanced efficiency of the sieve-tray spray scrubber was mostly between 20% and 60% in the experimental range. The higher efficiency of the sieve tray was found to be related not only to the foam height but also to the clear liquid foam height, which suggests that both the foam height and the gas holdup of the foam should be increased in order to increase the enhanced efficiency.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

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## AUTHOR CONTRIBUTIONS

WQ designed the study and revised it. WQ and Min Gu supervised and directed the project. WQ, WM, and Juan Wen performed the experiments. WQ and WM wrote the manuscript. CJ, WM, and LC revised the manuscript. WM revised the figure and gave support for the manuscript writing. All authors commented on the manuscript and gave final approval for publication.

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**Conflict of Interest:** Author WQ is employed by State Power Investment Corporation Yuanda Environmental Protection Engineering Co., Ltd.

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