Influence of Key Factors on the Characteristics of Flue Gas Desulfurization of Basic Aluminum Sulfate by Bubbles

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ABSTRACT: Temperature, reactant concentration, bubble flow field characteristics, and mass-transfer characteristics play an important role in flue gas desulfurization of basic aluminum sulfate (aluminum base). The influence of various factors on desulfurization efficiency ($\eta_{abs}$) was determined from the macroscopic and microscopic levels through experiments and numerical simulations. The temperature of absorption solution had a significant effect on $\eta_{abs}$ and low temperature was advantageous for $\eta_{abs}$ absorption performance of aluminum base. The value of $\eta_{abs}$ increased with increasing reactant concentration. When the aluminum base concentration was higher than 50%, $\eta_{abs}$ remained above 90%. The low aluminum base shortened the beginning time of the rapid decline of $\eta_{abs}$. This outcome was related to the low concentration of active Al₂O₃. At a low concentration range of 2000–5000 ppm of inlet SO₂, the reaction rate determined the $\eta_{abs}$ level, and gas-phase mass-transfer resistance was the main factor restricting the increase in $\eta_{abs}$. However, reaction rate and gas-phase mass-transfer resistance determined the $\eta_{abs}$ level when the inlet SO₂ concentration was as high as 50 000 ppm. The aeration rate affected the bubble size, number, and diffusion state. In addition, a higher aeration rate reduced the gas–liquid contact time and speeded up the consumption of aluminum base. As a result, bubbles along the absorber height showed different desulfurization characteristics, that is, 0–0.1 m was the initial stage of bubble formation and desulfurization (the $\eta_{abs}$ was lower than 15%), 0.1–0.34 m was the main stage of bubble diffusion and desulfurization (the $\eta_{abs}$ rapidly increased to 86.4%), and 0.34–0.4 m was the stable stage of desulfurization (the $\eta_{abs}$ slowly increased to 92.5%).

1. INTRODUCTION

Basic aluminum sulfate (aluminum base) desulfurization is a technology characterized by the use of renewable absorbent and SO₂ recyclability. Benefiting from the thermal desorption regeneration of absorbent, it reduced the limestone consumption due to aluminum base support and indirectly reduced the secondary pollution of CO₂ emissions from the traditional limestone gypsum desulfurization. In this process, preliminary studies at home and abroad mainly focused on the improvement of engineering parameters at the macrolevel in the 1940–1980s of the 20th century. Although this process exhibits high desulfurization efficiency ($\eta_{abs}$), the insufficiency of basic research on the physical and chemical mechanisms and quantitative relationship resulted in difficulties in engineering application. Since 2000, domestic scholars conducted experimental research on interactions among parameters and mainly discussed basic desulfurization characteristics under the static absorption system. Considering that bubble absorber exhibits the characteristics of simple structure, convenient operation, large interphase contact area, and good mass-transfer effect, studies must investigate the mechanism and characteristics of aluminum base desulfurization under this system for practical application.

Scholars have analyzed bubble characteristics and their influence on chemical processes. Yuan et al. studied the influence of height–diameter ratio of the bubble reactor and chemical reaction conditions on the flue gas decarburization performance of ammonia water; results concluded that increasing the ratio of height to diameter effectively increased the CO₂ absorption rate. Song et al. studied the bubble size, distribution, and local gas holdup rate under different aeration rates in a bubble column and obtained the probability density distribution of different bubble sizes. The bubble distribution increased with increasing axial height under high aeration rate. Yan et al. adopted the dynamic gas evolution method to examine the effects of liquid viscosity and operating conditions on bubble model parameters, such as bubble content, rising velocity, and total gas content, in the bubble column; the diameter of large bubbles increased slightly with increasing viscosity, whereas the diameter of small bubbles decreased dramatically. To explore the characteristics of seawater desulfurization, Qing and Xiao carried out desulfurization...
experiment of simulated exhaust gas on a ship on an independently designed jet bubble column system by changing parameters such as exhaust gas flow, seawater temperature, immersion depth, SO2 inlet concentration, and O2 concentration; the results revealed the relationship between exhaust gas flow rate and mass-transfer coefficient.

To apply a bubble absorber to desulfurization engineering, Bin et al.18,19 analyzed the process and operating parameters of the jet bubble column desulfurization technology in a domestic 600 MW thermal power plant. The effects of injection pipe immersion depth, inlet SO2 concentration, pH of the absorption solution, oxidation amount, agitation speed on SO2 removal efficiency, lime utilization rate, scaling conditions, and reliability were determined. Min20 experimentally studied the desulfurization of the bubble column in a 600 MW thermal power unit of Taishan Power Plant and found that the change in pH had greater effect on $\eta_{abs}$ than the change in liquid level.

Jin et al.21 experimentally investigated the reaction dynamic characteristics under bubble-type desulfurization tower in a 4.2 MW hot water boiler and used double-membrane theory to numerically calculate the $\eta_{abs}$ of flue gas. The results showed that $\eta_{abs}$ was sensitive to the inlet smoke temperature; that is, it increased with decreasing inlet smoke temperature.

Through numerical calculation of bubble column, Juan and Qin22 established a mathematical model of flue gas desulfurization (FGD) based on pilot-scale injection bubble reactor of whole mixed flow to determine component concentration, pH, and SO2 absorption rate. Considering the effect of bubble coalescence and fragmentation on bubble size, Guang et al.23,24 numerically simulated the gas−liquid two-phase flow in a bubble column reactor and evaluated reasonable axial velocity, gas holdup rate, and turbulent kinetic energy distribution.

At present, bubble-type absorption devices are mostly used for experiment or simulation of the physical flow field or chemical reaction characteristics of bubbles from a single aspect. Aluminum base desulfurization is a process with chemical mass transfer and involves chemical reaction and kinetic properties of interface zone. Macroscopic analysis alone is insufficient to comprehensively evaluate the unique properties of the interface and its vicinity. Thus, the interface needs to be studied from near microscopic experiments combined with microscopic analysis.25 The interface has wide applicability and reliability theoretically and is suitable to industrial application.

In this study, the influence of different factors on the desulfurization performance of aluminum base in a bubbler absorber was studied experimentally. The desulfurization mechanism of bubble formation, diffusion, and microscopic mass transfer during desulfurization was also investigated using numerical simulations accompanied by chemical reactions. This work provides theoretical reference for industrial application of aluminum base FGD by bubbles.

2. EXPERIMENT AND NUMERICAL SIMULATION

2.1. Experimental Method. The chemical reaction of aluminum base desulfurization is shown in eq 1

\[
(1 - x)\text{Al}_2(\text{SO}_4)_3 + 3x\text{SO}_2 \rightarrow \text{Al}_2\text{O}_3 + 3x\text{Al}_2(\text{SO}_4)_3
\]

The basic absorption solution was prepared and used as 100% concentration with an aluminum amount (amount of Al2O3 converted by aluminum ions) of 25 g/L and a basicity (x) of 25%. Then, the absorption solution with a fixed volume of 2000 mL in different concentrations could be obtained by adjusting the volume fraction of deionized water and basic absorption solution. Figure 1 shows the experimental apparatus system and related parameters. By controlling the volume flow of SO2 and air, different concentrations of simulated flue gas were prepared, and then, the aeration rate at the inlet of the absorber could be determined. At the same time, the absorber outlet SO2 concentration was measured by a flue gas analyzer. Thus, the experimental study was performed according to the scheme designed for experimental purpose.

In this system, the design of a front mixing cylinder and a rear buffer bottle was used to ensure a uniform absorber inlet SO2 concentration. The absorption experiment at different temperatures could be carried out by placing the absorber in a constant-temperature water bath (adjustable temperature) and
wrapping insulation layer outside. The formation and diffusion of bubbles were captured by high-speed cameras. \( \eta_{\text{abs}} \) was defined as shown in eq 2, where \( y_{\text{in}} \) and \( y_{\text{out}} \) are the mole (volume) fractions in ppm of \( \text{SO}_2 \) at the inlet and outlet of the absorber, respectively.

\[
\eta_{\text{abs}} = \frac{y_{\text{in}} - y_{\text{out}}}{y_{\text{in}}} \tag{2}
\]

Previous studies by the author showed that pH was the result of the combined effect of initial concentration of aluminum base solution and \( \text{SO}_2 \) absorption. Therefore, we selected temperature, aluminum base solution concentration, inlet \( \text{SO}_2 \) concentration, and aeration rate as the main factors to carry out the experimental research on the mechanism and performance of bubbling desulfurization with chemical mass transfer from the microlevel.

2.2. Simulation Method. In this paper, the simulation method was the same as that of previous publications of the author, in which ANSYS’s own mass equation, momentum equation, and energy equation were adopted to achieve numerical simulation. On the basis of the size of absorber, the physical model (Figure 2), meshing, and calculation domain were determined.

For the mathematical models, Euler-mixed model was selected to study the bubble flow field characteristics, and the volume of fluid mixed model was utilized to study the change of \( \text{SO}_2 \) concentration accompanied by the chemical reaction. Further, the pre-exponential factor, activation energy, and reaction rate constant were determined by kinetic experimental solving.

The main physical and chemical parameters are shown in Table 1.

| Parameter Name                      | Unit       | Numerical Value | Source            |
|-------------------------------------|------------|-----------------|-------------------|
| Atmospheric pressure                | kPa        | 100             | Selection         |
| Aeration rate                       | m/s        |                 | Experimental      |
| Inlet \( \text{SO}_2 \) concentration | mol/L     |                 | By flow regulation |
| Outlet \( \text{SO}_2 \) concentration | mol/L     |                 | Measurements      |
| Absorption solution concentration   | %          |                 | Experimental      |
| Gas density                         | kg/m³      | 1.225           | Selection         |
| Liquid density                      | kg/m³      | 998.2           | Selection         |
| Gas viscosities at 293, 308, and 323 K | Pa·s      | 1.72 × 10⁻⁵, 1.79 × 10⁻⁵, and 1.86 × 10⁻⁵ | Selection         |
| Liquid viscosities at 293, 308, and 323 K | Pa·s      | 1.1 × 10⁻⁵, 0.8 × 10⁻⁵, and 0.6 × 10⁻⁵ | Selection         |
| Pre-exponential factor              | s⁻¹        | 0.362           | Kinetic experiments |
| Activation energy                   | kJ/mol     | 1.56            | Kinetic experiments |
| Reaction rate constants at 293, 308, and 323 K | s⁻¹ | 0.191, 0.197, and 0.203 | Kinetic experiments |

In this way, the intrinsic link between relevant parameters in the desulfurization of aluminum base was established. This method provided the possibility of microscopic simulation of the desulfurization characteristics under bubbling conditions.

3. RESULTS AND DISCUSSION

3.1. Effect of Aluminum Base Absorption Solution Temperature on \( \eta_{\text{abs}} \). In order to investigate the effect of temperature on \( \eta_{\text{abs}} \) \( \text{SO}_2 \) absorption experiments at different temperatures were carried out under the conditions of absorption solution concentration of 50%, inlet \( \text{SO}_2 \) concentration of 5000 ppm, and aeration rate of 0.1 m/s. Figure 3 shows the effect of absorption solution temperature on \( \eta_{\text{abs}} \).

The temperature of absorption solution had a significant effect on \( \eta_{\text{abs}} \). Under different temperature conditions, \( \eta_{\text{abs}} \) showed different time-varying characteristics. When the
absorption temperature was reduced from 323 to 293 K, \( \eta_{abs} \) rapidly increased from 87.2 to 91.8\% in the initial absorption time (20 min). In addition, the time point at which \( \eta_{abs} \) began to decrease dramatically varied with the absorption temperature. In the experimental time range, \( \eta_{abs} \) under 293 K decreased slowly and remained at a higher level (91.8–90.2\%). At 308 K, \( \eta_{abs} \) decreased rapidly from 87.5 to 76\% with the absorption time from 180 to 260 min. However, at 323 K, \( \eta_{abs} \) showed a rapid downward trend from the initial absorption time and decreased from 87.2 to 53.8\% in 180 min. The reasons could be given as follows: high temperature reduced the SO\(_2\) solubility and also provided temperature conditions for the SO\(_2\) desorption of aluminum base absorption solution, which in turn had a negative impact on \( \eta_{abs} \). The cumulative effect of SO\(_2\) escape caused by the combination of temperature level and time determined the variation of \( \eta_{abs} \) under different temperature conditions. Hence, a low temperature was advantageous for the SO\(_2\) absorption performance of aluminum base.

**3.2. Effect of Aluminum Base Absorption Solution Concentration on \( \eta_{abs} \).** At an absorption solution temperature of 293 K, both the simulated flue gas SO\(_2\) concentration of 5000 ppm and aeration rate of 0.1 m/s were selected for experiments. Figure 4 shows the effect of absorption solution concentration on \( \eta_{abs} \).

![Graph showing the effect of absorption solution concentration on \( \eta_{abs} \).](image)

**Figure 4.** Effect of absorption solution concentration on \( \eta_{abs} \). T, 293 K; inlet SO\(_2\) concentration, 5000 ppm; and aeration rate, 0.1 m/s.

When the concentration of aluminum base absorption solution changed from 25 to 100\%, the \( \eta_{abs} \) range was from 78.9 to 93.7\%. Under the same desulfurization time, \( \eta_{abs} \) increased with the increase of aluminum base concentration but showed different time variation characteristics at different aluminum base concentrations.

The experiment showed that \( \eta_{abs} \) remained at a high level of more than 90\% at aluminum base concentration higher than 50\%. \( \eta_{abs} \) maintained stability at approximately 91\% and decreased slowly from 91.1 to 90.2\% after 260 min at an aluminum base concentration of 50\%. When aluminum base concentration was 100\%, \( \eta_{abs} \) remained stable at approximately 93\% and decreased slowly from 93.5 to 92.9\% after 300 min. By contrast, the overall \( \eta_{abs} \) level was low at aluminum base concentration less than 50\%, and \( \eta_{abs} \) was less than 86.4\% at an aluminum base concentration of 25\%. At the same time, \( \eta_{abs} \) decreased slowly from 85.9 to 84.2\% at the interval of 120–260 min and then declined rapidly to 78.9\%. This result was related to the low concentration of active Al\(_2\)O\(_3\) in the low concentration of aluminum base absorbing solution.

**3.3. Effect of Inlet SO\(_2\) Concentration on \( \eta_{abs} \).** The emission range of SO\(_2\) was 0–5000 ppm in coal–fired power plant and 15 000–80 000 ppm in smelting flue gas. Meanwhile, the higher concentration might make the difference of mass-transfer characteristics and \( \eta_{abs} \) more significant. We selected the inlet SO\(_2\) concentration of 2000, 5000, and 50 000 ppm as the desulfurization object. Then, aluminum base desulfurization experiments were performed with the absorption solution temperature of 293 K, aluminum base concentration of 50\%, and aeration rate of 0.1 m/s.

Figure 5 shows the effect of inlet SO\(_2\) concentration on \( \eta_{abs} \).

![Diagram showing the effect of inlet SO\(_2\) concentration on \( \eta_{abs} \).](image)

**Figure 5.** Effect of inlet SO\(_2\) concentration on \( \eta_{abs} \). T, 293 K; absorption solution concentration, 50\%; and aeration rate, 0.1 m/s.

When the inlet SO\(_2\) concentration changed from 2000 to 50 000 ppm, the overall \( \eta_{abs} \) remained at a high level over 90\%. Meanwhile, \( \eta_{abs} \) increased with the increase of aluminum base concentration under the same desulfurization time. However, \( \eta_{abs} \) showed different time variation characteristics at different inlet SO\(_2\) concentrations. Experiments showed that \( \eta_{abs} \) was relatively low under the low inlet SO\(_2\) concentration of 2000–5000 ppm. When the concentration was 2000 and 5000 ppm, \( \eta_{abs} \) was stable at approximately 90 and 91\%, respectively. However, \( \eta_{abs} \) decreased slowly from 91.1 to 90.2\% after 260 min under the inlet SO\(_2\) concentration of 5000 ppm. From the analysis above, the chemical reaction rate determined the \( \eta_{abs} \) level, and the gas-phase mass-transfer resistance was the main factor restricting the \( \eta_{abs} \) increase under this low SO\(_2\) concentration condition. Under the condition of high inlet SO\(_2\) concentration of 50 000 ppm, the increase of reaction rate and SO\(_2\) gas-phase mass-transfer power led to a high \( \eta_{abs} \) level of 94.9\% in the initial stage (within 140 min) but accelerated the consumption of active Al\(_2\)O\(_3\) in aluminum base absorption solution. Thus, \( \eta_{abs} \) decreased slowly from 94.7 to 93.6\% at the interval of 140–280 min and then declined rapidly to 91.1\%. As a result, the chemical reaction rate and gas-phase mass-transfer resistance together determine the \( \eta_{abs} \) level under this high SO\(_2\) concentration condition.

In general, higher SO\(_2\) concentration was beneficial to enhance gas-phase mass-transfer capacity and increase reaction
rate. Considering the objectivity of SO$_2$ emission concentration of coal-fired flue gas under different industrial conditions, strengthening the gas–liquid mass transfer by physical methods was one of the main ways to effectively improve the $\eta_{abs}$ of bubbling desulfurization.

3.4. Effect of Aeration Rate on $\eta_{abs}$. Under the condition of absorption solution temperature of 293 K, the experiment was conducted at a simulated flue gas SO$_2$ concentration of 5000 ppm and an aluminum base absorption solution concentration of 50%. Figure 6 shows the effect of absorber inlet aeration rate on $\eta_{abs}$.

When the aeration rate was changed from 0.05 to 0.15 m/s, the $\eta_{abs}$ range was from 89.7 to 93.2%. At the same desulfurization time, $\eta_{abs}$ increased with the aeration rate. For each aeration rate, a stable segment and different maintenance times for high $\eta_{abs}$ were observed. The experiments showed that $\eta_{abs}$ remained stable by approximately 90% at the aeration rate of 0.05 m/s. However, $\eta_{abs}$ decreased slowly from 91.1 to 90.2% after 260 min at the aeration rate of 0.1 m/s. Moreover, $\eta_{abs}$ decreased slowly from 93 to 92.6% at the interval of 120–220 min at the aeration rate of 0.15 m/s and then declined rapidly to 90.6%.

These results above might be related to the high aeration rate reducing the stagnation time of bubbles in liquid phase. Moreover, higher aeration rate might enhance the gas–liquid mass transfer, but it would consume more absorbents, resulting in shorter time with high $\eta_{abs}$ level. Therefore, under the same reactant concentration conditions, the hydrodynamic field characteristics had an important influence on $\eta_{abs}$.

3.5. Numerical Simulation Microscopic Analysis of Alumina Base Desulfurization. The bubble aluminum base desulfurization was completed gradually as the bubbles diffuse in the height direction. Observation of the bubble formation, diffusion, and SO$_2$ concentration changes in the height direction of the absorber showed that the gas–liquid absorption mass-transfer characteristics accompanied by chemical reactions could be comprehensively analyzed and judged from the microscopic level.

Given that the high inlet SO$_2$ concentration and low aluminum base concentration could quickly and clearly reflect the $\eta_{abs}$ changes, we selected the inlet SO$_2$ concentration of 50 000 ppm as the desulfurization object. Then, aluminum base desulfurization experiment was simulated at the temperature of 293 K, absorption solution concentration of 25%, and aeration rates of 0.05, 0.1, and 0.15 m/s. Through this method, the microscopic law of desulfurization chemical mass transfer could be revealed.

3.5.1. Effect of Bubble Formation and Diffusion on Chemical Mass Transfer. Figure 7 shows the initial bubble size at different aeration rates. With the increase of aeration rate, the formation of the initial bubble decreased first and then increased.

Small aeration rate resulted in larger initial bubble and greater buoyancy than the bubble gravity and viscous force of the orifice. At this time, the effect of bubble orifice separation was mainly controlled by viscous force of the orifice. As the aeration rate increased, the initial bubble diameter became small, causing a decrease in buoyancy and orifice viscous force. At this point, the thrust generated by the aeration rate became the driving force for bubble diffusion, and the effect of bubble orifice separation was mainly controlled by the aeration rate. The large aeration volume increased the bubble diameter again when the aeration rate increases to a certain critical value (0.15 m/s). At this time, the effect of bubble orifice separation was controlled together by the aeration rate and viscous force of the orifice. The result above was consistent with the study of Dou.31

Figures 8 and 9 show the rising and diffusing states of the initial bubble every 2 s at the aeration rate of 0.05 m/s.

The rising and diffusing of bubbles were affected by static pressure, buoyancy, surface tension, fluid turbulence, and shearing force. Thus, the bubble underwent multiple coalescence and breakage, and its size and morphology changed irregularly. Meanwhile, the bubble breaks when subjected to an external force greater than the surface tension. During bubble collision, the liquid in the liquid film flowed out
to make the liquid film thin and fused under the combined effect of surface tension and siphon action.\textsuperscript{32,33}

On the one hand, the bubble diffused axially along the height direction under the action of velocity. On the other hand, a horizontal velocity was generated, and the radial diffusion zone of bubbles began to form at a certain height under the combined action of liquid hydrostatic pressure, hydrodynamic pressure, and shear stress. This condition promoted the degree of mixing in the gas–liquid phase and provided physical mass-transfer power for the full SO\textsubscript{2} reaction with the aluminum base. Under this experimental system, the bubbles evolved in the height direction of the absorber in the form of a single gas column (about 1/4 height at the bottom) to the crushing and mixing, and then the large bubble (about 1/4 height in the upper part).

Furthermore, the effect of aluminum base desulfurization with a chemical reaction not only depended on the physical mass transfer but also on the absorption reaction of SO\textsubscript{2}. This phenomenon could be explained by the microscopic process of SO\textsubscript{2} absorption in bubbles.

Figure 10 shows both the bubble coalescence and SO\textsubscript{2} concentration distribution in the aluminum base absorption solution. Combined with the analysis of two-film theory, we could see that the SO\textsubscript{2} gradually diffused from the gas phase to the liquid phase, thereby forming a stable gas–liquid boundary film. The chemical reaction of aluminum base desulfurization mainly occurred in the gas–liquid boundary film. This result was related to the fast desulfurization reaction of the aluminum base.

The distribution of SO\textsubscript{2} partial pressure (or concentration) in the gas film determined the difference in mass-transfer resistance. During the entire chemical mass transfer, SO\textsubscript{2} diffused from the gas phase through the gas–liquid boundary film into the liquid phase by molecular diffusion and then formed a certain concentration gradient. At a stable reaction, no mass-transfer resistance was observed at the phase interface, or the gas–liquid phase reached the concentration balance. In the gas–liquid phase main body outside the stagnant film, given that the gas–liquid phase could not directly contact and mass transfer, no concentration gradient was observed. The material composition was also uniform and stable. The above conclusion was consistent with the previous research of the author.\textsuperscript{27}

Overall, the performance of bubble aluminum base desulfurization was influenced by both the chemical reaction rate and the gas-phase mass-transfer capacity. Therefore, increasing the number of small bubbles while promoting the disturbance of the flow field to improve the mass-transfer driving force could increase the gas–liquid contact area of the chemical reaction and improve $\eta_{abs}$.

3.5.2. Microscopic Process of Aluminum Base Desulfurization. The microscopic process of aluminum base desulfurization performance could be obtained by analyzing the SO\textsubscript{2} average concentration in the absorber height direction. At different aeration rate conditions, $\eta_{abs}$ at the outlet of the absorber was selected at a certain point in the stable stage. This factor served as the basis for the simulation results and experimental comparison. Figures 11 and 12 show the comparison of the simulated values of SO\textsubscript{2} average concentration and $\eta_{abs}$ along the absorber height with the experimental values at the time of 6 min.

At the aeration rates of 0.05, 0.1, and 0.15 m/s, the simulated value of $\eta_{abs}$ at the outlet of the absorber had a good agreement with the experimental value, and the relative errors were $-2.54$, $-4.02$, and $-2.90\%$, respectively.

The interval of 0–0.1 m in height was the initial stage of bubble formation and aluminum base desulfurization. At this stage, the initial bubbles entering the liquid phase were more concentrated, and the effective contact surface with absorption solution was small. Meanwhile, the large liquid pressure
hindered the bubble diffusion in the gas phase. This condition resulted in the inability of gas–liquid interaction to proceed rapidly. Thus, the SO₂ average concentration in gas phase was high, and \( \eta_{abs} \) was only 15% or less.

The interval of 0.1–0.34 m in height was the main stage for bubble diffusion and aluminum base desulfurization. At this stage, a large number of bubbles of different sizes continuously rose and diffused. On the one hand, the reduction of the mixing pressure of the gas–liquid phase decreased the mass-transfer resistance at the phase interface. Meanwhile, the increase of effective contact area promoted the chemical mass transfer. At this time, the SO₂ average concentration decreased rapidly with height, and \( \eta_{abs} \) corresponding to the aeration rates 0.05, 0.1, and 0.15 m/s increased rapidly to 84.8, 86.4, and 85.9%, respectively.

The interval of 0.34–0.4 m in height was the stable stage for aluminum base desulfurization. At this stage, the number of bubbles was small, the size was large, and the SO₂ concentration in bubbles was low. This phenomenon decreased the gas–liquid mass-transfer capacity and the chemical reaction rate. At this time, the SO₂ average concentration gradually decreased to a low level. In addition, \( \eta_{abs} \) corresponding to the aeration rates 0.05, 0.1, and 0.15 m/s slowly increased to 89.8, 92.5, and 92.2%, respectively.

4. CONCLUSIONS

The characteristics for aluminum base FGD were comprehensively examined by combining bubbling SO₂ absorption experiments and numerical simulations under various factors. The results showed that the desulfurization performance was affected by both the chemical reaction rate and gas-phase mass-transfer capacity. The temperature of absorption solution had a significant effect on \( \eta_{abs} \) and low temperature was advantageous for SO₂ absorption performance of aluminum base. Effectively increasing the number of small bubbles could improve the bubble diffusion and promote the disturbance of the flow field to improve the mass-transfer driving force. At the same time, the gas–liquid contact area of the chemical reaction was increased and promoted the \( \eta_{abs} \) increase. During desulfurization, three stages exist, namely, the initial desulfurization zone with bubble formation (\( \eta_{abs} \) was low), the core desulfurization zone with bubble diffusion (\( \eta_{abs} \) increased rapidly), and the stable desulfurization zone (\( \eta_{abs} \) was high and stable). The effect of absorption temperature on desulfurization performance was that \( \eta_{abs} \) decreased with the rise of temperature under the same desulfurization time. The stabilization time of high \( \eta_{abs} \) was markedly shortened with the increase of absorption temperature from 293 to 323 K; especially at 323 K, the \( \eta_{abs} \) decreased rapidly from 87.2% at the beginning to 53.8% within 180 min. The effect of absorption solution concentration on desulfurization performance was that \( \eta_{abs} \) increased with the increase of aluminum base concentration under the same desulfurization time. When the concentration range of aluminum base was greater than 50%, \( \eta_{abs} \) remained above 90%. Meanwhile, the overall level of \( \eta_{abs} \) was low when the concentration range was less than 50%. The effect of inlet SO₂ concentration on desulfurization performance was that \( \eta_{abs} \) increased with the increase of inlet SO₂ concentration under the same desulfurization time. Under the conditions of aluminum base concentration of 50% and inlet SO₂ concentration higher than 2000 ppm, \( \eta_{abs} \) was above 90%. Although high inlet SO₂ concentration was beneficial to increase \( \eta_{abs} \), it also shortened the \( \eta_{abs} \) maintenance time. The effect of aeration rate on desulfurization performance was that \( \eta_{abs} \) increased with the aeration rate under the same desulfurization time. The aeration rate affected not only the size formation and diffusion state of bubbles in liquid phase but also the effective gas–liquid contact time and aluminum base consumption rate in the finite absorber. Therefore, an optimal aeration rate was observed for a given desulfurization system.

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