Postprint of Experimental Study on Flow Pulsation Characteristics in a Pressurized Liquid Curtain Bed

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Abstract

This study designed and constructed a pressure monitoring experimental system for a pressurized liquid curtain bed. By adjusting parameters such as gas-liquid flow rate and working pressure in the pressurized liquid curtain bed, the flow characteristics were investigated with particular emphasis on analyzing the pressure difference fluctuation characteristics and the variation patterns of the resistance coefficient. Through combining experimental data and theoretical analysis, the variation patterns of pressure difference fluctuation intensity and resistance coefficient under different gas-liquid flow rates and working pressures were obtained, and the optimal operating parameters were analyzed in conjunction with the principles of gas-liquid absorption reaction for flue gas desulfurization. This research can provide important design references for the industrial application of pressurized liquid curtain bed gas-liquid reaction systems.

Full Text

Preamble

Title: Experimental Research on Flow Pulse Characteristics of Pressurized-Liquid-Screen Bed

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Abstract: This paper presents the design and construction of an experimental pressure monitoring system for a pressurized-liquid-screen bed. The flow characteristics were investigated by adjusting gas flow rate, liquid flow rate, and operating pressure parameters, with particular emphasis on analyzing differential pressure pulsation characteristics and resistance coefficient variations. Through combined experimental data and theoretical analysis, the variation patterns of pressure pulsation intensity and resistance coefficients under different gas-liquid flow rates and operating pressures were determined. Additionally, optimal operating parameters were analyzed based on the principles of flue gas desulfurization gas-liquid absorption reactions. This research provides crucial design references for the industrial application of pressurized-liquid-screen gas-liquid reaction systems.

Keywords: Pressurized-liquid-screen; Pulse Intensity; Differential Pressure; Resistance Coefficient

Gas-liquid interaction is a critical factor affecting gas-liquid absorption efficiency. To enhance this interaction, various approaches have been studied: Tsinghua University investigated the performance and influencing factors of liquid column injection technology based on the traditional "spray method" [1]; Zhejiang University proposed an impinging liquid column device [2,3]; the University of Petroleum studied the flow characteristics and mass transfer process between gas and liquid phases in a liquid column tower, discovering regions with sharp pressure gradient changes that are key locations for flue gas desulfurization [4]; Xi' an Jiaotong University proposed a liquid-screen gas-liquid two-phase flow pattern that combines the advantages of spray, liquid column, and bubbling bed technologies [5-8]. Building upon the liquid-screen bed, this paper introduces a pressurized-liquid-screen bed that increases gas-phase operating pressure to enhance gas mass flow rate, thereby increasing gas-liquid contact and improving gas-liquid heat and mass transfer efficiency. The gas-phase flow pulsation characteristics in the gas-liquid interaction section are important parameters affecting desulfurization efficiency. To systematically investigate the influence of differential pressure and its pulsation and resistance coefficients on gas-liquid interaction, an experimental pressure monitoring system for the pressurized-liquid-screen bed was constructed. Experimental data and theoretical analysis can provide theoretical foundations for improving gas-liquid two-phase flow interaction in pressurized-liquid-screen beds and offer important references for parameter design in industrial applications.

1 Experimental System

The experiments were conducted on a pressurized-liquid-screen bed pressure monitoring experimental platform. The schematic diagram of the experimental system is shown in [Figure 1: see original paper]. The platform consists of an upper absorption section and a lower mixing section. In the absorption section, the circulating slurry contacts the flue gas fully; in the mixing section, the slurry after gas-liquid interaction mixes with fresh slurry. A counter-current absorption tower was used, where the gas flow direction is opposite to the liquid falling direction. To facilitate observation of the flow state inside the liquid-screen bed, the tower body was made of an 11 mm thick, 110 mm diameter plexiglass tube. The tower height is 1000 mm, with an internal channel cross-section of 88 mm diameter. Slurry nozzles are arranged at the lower part of the absorption tower. The nozzle array adopts a divergent equidistant arrangement. This study used a 2$×$8 nozzle array with 16 nozzles, as shown in [Figure 2: see original paper].

The liquid circulation system supplies the absorption liquid and recycles it. Water was used to simulate slurry in this study. The liquid circulation system consists of a slurry tank, circulation pump, valves, electromagnetic flowmeter, and splash guard. Liquid flow rate was measured by an LD-15/Y/ZA/AC/If/N/T2/PTFE/316L electromagnetic flowmeter with a range of 0.2 $\mathrm{m}^3 \cdot \mathrm{h}^{-1}$ to 6.0 $\mathrm{m}^3 \cdot \mathrm{h}^{-1}$ and accuracy of Class 1.

The flue gas system supplies simulated flue gas and facilitates gas-liquid contact. Air was used to simulate flue gas in this study. The flue gas system consists of an air compressor, control valves, flue gas duct, gas turbine flowmeter, etc. Gas flow rate was measured by an LWQ-40E gas turbine flowmeter with a range of 3 $\mathrm{m}^3 \cdot \mathrm{h}^{-1}$ to 60 $\mathrm{m}^3 \cdot \mathrm{h}^{-1}$ and accuracy of Class 1.5. After gas-liquid contact, the gas is discharged into the atmosphere.

The pressure difference measurement system uses a CYB21 micro-pressure differential transmitter from Xi' an Xinmin Electronics, with a measurement range of 0–1.5 kPa, accuracy of 0.3%, output signal of 4–20 mA, and response time less than 1 ms. The power supply uses an Atten APR3002A. Pressure pulsation data acquisition was performed using a National Instruments (NI) PCI-6013 card with a sampling rate of 200 kS/s/Ch and resolution of 16 bit.

This study selected the 2$×$8 nozzle array and conducted experiments across a range of gas-phase pressures and gas flow rates. Since the gas phase significantly affects the liquid-screen bed height, and the liquid flow rate varied considerably throughout the experiments, it was difficult to control a constant liquid flow rate for investigation. Therefore, ten uniform bed height regions were selected in the experimental section. When the bed height stabilized in a corresponding region, the liquid flow rate was immediately recorded for analysis.

2 Data Analysis Methods

Probability Density Function (PDF) analysis is a time-domain method that describes the probability distribution of random variables. If a function f exists such that for all x in the interval, the following condition holds: $f(x) \geq 0$. For a set $A = \{x | a \leq x \leq b\}$, the probability can be approximated by:

$$P(A) = \int_a^b f(x) dx$$

where Δx is the class interval, P_i is the probability of group i, which can be calculated by:

$$P_i = \frac{n_i}{N}$$

where n_i is the frequency of sample point x_i, and N is the total number of sample points in the population.

For steady flow, when the fluctuating signal is sampled over a sufficiently long time period, the resulting probability density function becomes time-independent [11]. This paper characterizes the flow pulsation in the pressurized-liquid-screen bed gas-liquid two-phase flow using five parameters: differential pressure pulsation range, mean differential pressure pulsation, differential pressure pulsation peak, differential pressure pulsation uniformity, and resistance coefficient.

The differential pressure distribution range ΔP_l is defined as the range of gas-phase differential pressure in the absorption tower. The mean differential pressure pulsation ΔP_a is defined as the average of all differential pressure data values collected per unit time in the absorption tower. The pulsation peak differential pressure ΔP_p is defined as the differential pressure value corresponding to the PDF peak.

3 Theoretical Model Analysis

As shown in [Figure 3: see original paper], the trajectory of a single liquid particle in the absorption tower is divided into five regions: A, B, C, D, and E. These regions are not absolute spatial positions; their division depends on the liquid particle velocity v_s, gas absolute velocity v_g, gas-liquid relative velocity, terminal settling velocity s_z, and liquid particle diameter d_s. Region A is where liquid particle velocity v_s exceeds gas velocity v_g. Region B is where gas velocity v_g exceeds liquid particle velocity v_s. Region C is the liquid particle acceleration zone, which is significantly influenced by particle diameter d_s; larger particles cover a wider range in region C. In region D, particles detach from the bed due to their own pulsation and gas-phase action. In region E, particles reach terminal settling velocity s_z and move at constant speed.

The injected liquid flows in the same direction as the gas before reaching its apex, and flows counter-current after reaching the apex. During the upward motion, when liquid particle velocity v_s is high (region A in [Figure 3: see original paper]), the liquid accelerates the gas, reducing the gas-phase differential pressure in the experimental section to some extent. When liquid particle velocity v_s is low (region B in [Figure 3: see original paper]), the liquid hinders gas motion, increasing the gas-phase differential pressure. During the falling process (region C in [Figure 3: see original paper]), the hindrance effect on gas flow increases with falling distance for droplets that have not reached the critical diameter. For droplets that have reached the critical diameter, this hindrance effect no longer increases (regions D and E in [Figure 3: see original paper]).

When gas-phase pressure increases, the gas mass flow rate W, density ρ, and kinematic viscosity coefficient μ all increase. Consequently, the gas kinetic energy and momentum increase, enhancing the impact and entrainment effects on the liquid. Simultaneously, the buoyancy force f_b on the liquid in the absorption section increases, terminal settling velocity s_z decreases, and critical diameter d_z increases. These changes promote the coalescence of small liquid particles, causing more liquid particles to combine into larger droplets after entering region D, thereby increasing gas-liquid contact quantity and contact time. These combined effects increase the gas-phase differential pressure and its pulsation intensity.

4.1.1 Differential Pressure Pulsation Analysis

The gas-phase differential pressure pulsation in the pressurized-liquid-screen bed absorption section is influenced by both gas and liquid phases. The pulsation caused by liquid injection is directly generated by gas-liquid interaction, while pulsation from gas-phase motion can also enhance gas-liquid contact and mixing. Since data acquisition in this study used equal sample counts per unit time, each PDF analysis contained the same number of data points. Therefore, the differential pressure pulsation range ΔP_l can represent the possible range of differential pressure values under current operating conditions, while PDFmax can indicate the concentration degree of differential pressure distribution. These two parameters reflect differential pressure pulsation intensity, which is positively correlated with ΔP_l and negatively correlated with PDFmax.

Using data from the sixth region in the operating conditions, the differential pressure probability density function (PDF) analysis results for different gas flow velocities are shown in [Figure 4: see original paper]. Under the same gas-phase pressure (P = 0.3 MPa) and gas flow velocity (v_g = 1.80 $\mathrm{m \cdot s^{-1}}$), the PDF analysis results for different liquid injection velocities are shown in [Figure 5: see original paper]. Under the same gas flow velocity (v_g = 1.80 $\mathrm{m \cdot s^{-1}}$) and liquid injection velocity (data corresponding to the sixth bed height region), the PDF analysis results for different gas-phase pressures are shown in [Figure 6: see original paper]. The variation of differential pressure pulsation range ΔP_l with liquid injection velocity under different gas-phase pressures is shown in [Figure 7: see original paper].

The following patterns were observed: 1. At low gas flow velocities, PDFmax is high, ΔP_p is low, and ΔP_l is small, resulting in weak differential pressure pulsation intensity. As v_g increases, the PDF curve shifts rightward, PDFmax decreases, ΔP_p increases significantly, and ΔP_l expands. Differential pressure pulsation intensity is positively correlated with gas flow velocity. 2. As liquid injection velocity increases, the PDF curve shifts slightly rightward with a relatively stable shape. ΔP_p increases while other pulsation intensity parameters remain essentially stable, indicating that differential pressure pulsation intensity is almost unaffected by liquid injection velocity. 3. At low gas-phase pressures, PDFmax is high, ΔP_p is low, and ΔP_l is small. As gas-phase pressure increases, PDFmax decreases, the pulsation peak differential pressure increases slightly, and the differential pressure pulsation range increases substantially with intensified fluctuations. Differential pressure pulsation intensity is positively correlated with gas-phase pressure.

4.1.2 Mean Differential Pressure Pulsation Analysis

Figure 8: see original paper shows the relationship between mean differential pressure pulsation ΔP_a and liquid injection velocity v_l at the same gas flow velocity but different gas-phase pressures. As v_l increases, ΔP_a first increases then decreases, with this phenomenon being more pronounced at lower gas flow velocities. The injection velocity corresponding to the inflection point of pressure change is lower at lower gas flow velocities. As gas-phase pressure increases, the differential pressure in the experimental section rises significantly.

Figure 8: see original paper shows the relationship between ΔP_a and v_l at the same gas-phase pressure but different gas flow velocities. As v_l increases, ΔP_a first increases then decreases. This phenomenon is more evident at lower gas flow velocities, and the injection velocity corresponding to the inflection point is lower. As gas flow velocity increases, the differential pressure in the experimental section increases significantly.

When v_l is low, only region B exists during the upward process, where liquid hinders gas motion. During the falling process, most particles cannot reach terminal settling velocity s_z. As v_l increases, liquid still hinders gas motion during upward movement, but the hindrance effect from falling droplets continues to increase, causing ΔP_a to rise. When v_l continues to increase, region A appears while a certain number of falling droplets enter region E and reach s_z, slowing the rate of ΔP_a increase until it reaches a peak. As v_l continues to increase further, region A expands, region C expands but at a slower rate, and region E expands, causing ΔP_a to decrease.

When v_g increases, the v_l required for region A formation and expansion increases, so the injection velocity corresponding to the inflection point of the pressure curve is higher. When gas-phase pressure increases, region A forms and expands more easily while s_z decreases, so the injection velocity corresponding to the inflection point is lower, indicating more significant gas-liquid interaction.

4.2 Resistance Coefficient Analysis

The resistance coefficient of the gas-liquid reaction section is an important factor affecting flue gas desulfurization efficiency, industrial application design, and economic viability. Strong gas-liquid interaction inevitably increases resistance to gas flow, which relates to fan efficiency and energy consumption. Therefore, analyzing the resistance coefficient can provide design basis for industrial desulfurization tower applications and, more importantly, help find the balance point between improving desulfurization efficiency and enhancing power plant operational economy.

The overall resistance coefficient of the absorption section in the experiments is calculated as:

$$\varepsilon = \frac{\Delta P}{\rho v^2}$$

where ΔP is the flue gas pressure drop in the absorption tower (Pa), ρ is gas density ($\mathrm{kg \cdot m^{-3}}$), and v is gas velocity ($\mathrm{m \cdot s^{-1}}$).

Figure 9: see original paper shows the relationship between the experimental section resistance coefficient ε and liquid injection velocity v_l at the same gas flow velocity but different gas-phase pressures. As v_l increases, ε first increases then decreases. As gas-phase pressure increases, ε decreases significantly. Figure 9: see original paper shows the relationship between ε and v_l at the same gas-phase pressure but different gas flow velocities. As v_l increases, ε first increases then decreases. The lower the v_g, the lower the injection velocity corresponding to the inflection point of ε. When v_l is less than 2.0 $\mathrm{m \cdot s^{-1}}$, lower gas flow velocities correspond to smaller ε values. When v_l exceeds 2.0 $\mathrm{m \cdot s^{-1}}$, lower gas flow velocities correspond to larger ε values. The region around $v_l = 2.0\ \mathrm{m \cdot s^{-1}}$ represents an intersection area for multiple curves in the figure.

The variation of total resistance f on the gas phase in the experimental section directly reflects changes in the resistance coefficient ε. At low v_l, region C appears and continuously expands while region A has not yet formed, causing the liquid-induced resistance f_w to increase continuously. As v_l continues to increase, region A appears and expands, region C expands but at a slower rate, and region E appears and expands, causing f_w to continue increasing but at a slower rate. When v_l increases to a certain value, region A continues to expand, region C stabilizes, and region E continues to expand, causing f_w to reach a peak and then decrease.

Without liquid injection in the absorption section, the total experimental section resistance f primarily comes from frictional resistance f_L and local resistance f_j, which are determined by the experimental section structure and gas flow velocity. When the experimental section structure remains unchanged, f_L and f_j are proportional to gas flow velocity v_g, so lower v_g corresponds to lower total experimental section resistance coefficient ε. At the beginning of low-velocity liquid injection, the liquid’ s effect on the gas phase is weak, and gas flow behavior is similar to the empty condition. When v_l is around 2.0 $\mathrm{m \cdot s^{-1}}$, the liquid’ s hindrance effect on gas motion begins to strengthen. Since liquid velocity is still relatively low at this point, region A does not exist, and region C has a significant impact on gas motion. Lower-velocity gas has lower kinetic energy and is more affected by falling liquid, causing the resistance coefficient to increase rapidly under low gas flow velocity. Since region A appears and expands at lower liquid injection velocities under low gas flow velocity, the v_l corresponding to its ε peak is also lower.

In the right-side region of the ε-v_l curve inflection point in [Figure 9: see original paper], ε decreases sharply with increasing v_l, which can reduce fan energy consumption, but large liquid injection volumes also increase pump energy consumption. Additionally, the mean differential pressure pulsation decreases sharply with increasing v_l, which is unfavorable for gas-liquid interaction. In the left-side region of the curve, achieving the corresponding mean differential pressure pulsation requires only a small liquid injection velocity. Based on the conclusion from Section 4.1.1 that differential pressure pulsation intensity is almost unaffected by v_l, the optimal operating parameters for the pressurized-liquid-screen bed absorption tower should be selected from the left side of the ε-v_l curve inflection point.

Conclusions

This study utilized a pressurized-liquid-screen bed pressure monitoring experimental platform to investigate the flow pulsation characteristics of gas-liquid two-phase flow in pressurized-liquid-screen beds, combining theoretical modeling with experimental data analysis. The following conclusions were obtained:

1. The trajectories of injected droplets in the pressurized-liquid-screen bed can be divided into five regions, with the division depending on liquid particle velocity v_s, gas absolute velocity v_g, gas-liquid relative velocity, terminal settling velocity s_z, and liquid particle diameter d_s. In region A, $v_s > v_g$; in region B, $v_g > v_s$; in region C, liquid particles accelerate downward, significantly influenced by d_s; in region D, particles detach from the bed; and in region E, particles move at constant velocity after reaching s_z.

2. As gas flow velocity v_g increases, the mean differential pressure pulsation ΔP_a and differential pressure pulsation intensity both increase. As gas-phase pressure increases, both ΔP_a and differential pressure pulsation intensity increase. ΔP_a first increases then decreases with increasing liquid injection velocity v_l, while differential pressure pulsation intensity is essentially independent of v_l.

3. As gas flow velocity v_g increases, both the mean resistance coefficient and its distribution range decrease. At low gas flow velocities, the mean resistance coefficient decreases while its distribution range increases with gas-phase pressure. At higher gas flow velocities, both the mean resistance coefficient and its distribution range remain essentially stable as gas-phase pressure increases. The resistance coefficient ε first increases then decreases with increasing liquid injection velocity v_l.

4. The optimal operating parameters for the pressurized-liquid-screen bed absorption tower should be selected from the left side of the ε-v_l curve

inflection point.

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