

Experimental Study on Flow Pulsation Characteristics of Pressurized Liquid Curtain Bed (Post-print)

Authors: Hu Zhengtao, Li Lian, Li Na, Zhou Qulan

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Abstract

This study designs and constructs a pressure monitoring experimental system for a pressurized liquid curtain bed, and by adjusting parameters such as gas-liquid flow velocities and operating pressure within the bed, investigates the flow characteristics with particular emphasis on analyzing pressure differential fluctuation characteristics and the variation patterns of the resistance coefficient. Through integration of experimental data and theoretical analysis, the variation patterns of pressure differential fluctuation intensity and resistance coefficient under different gas-liquid flow velocities and operating pressures are elucidated, and the optimal operating parameters are analyzed based on the principles of flue gas desulfurization gas-liquid absorption reactions. 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

Authors: HU Zheng-Tao, LI Lian, LI Na, ZHOU Qu-Lan

Affiliation: State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

Abstract: This paper designs and constructs an experimental pressure monitoring system for a pressurized liquid-screen bed. By adjusting gas-liquid flow rates and operating pressure parameters, the flow characteristics within the pressurized liquid-screen bed are investigated, with particular emphasis on analyzing

differential pressure pulsation characteristics and resistance coefficient variation patterns. Through combined experimental data and theoretical analysis, the variation principles of pressure pulsation intensity and resistance coefficient under different gas-liquid flow rates and operating pressures are revealed, and optimal operating parameters are 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 bed gas-liquid reaction systems.

Keywords: Pressurized liquid-screen bed; Pulse intensity; Differential pressure; Resistance coefficient

Introduction

Gas-liquid interaction is a critical factor affecting gas-liquid absorption efficiency. To enhance this interaction, researchers have built upon traditional spray methods: Tsinghua University investigated liquid column injection technology performance and related influencing factors [1]; Zhejiang University proposed an impinging liquid column device [2,3]; the University of Petroleum studied gas-liquid flow characteristics and mass transfer processes in liquid column towers, identifying regions with sharp pressure gradient changes as key locations for sulfur absorption [4]; Xi'an Jiaotong University introduced the liquid-screen gas-liquid two-phase flow, which combines advantages of spray, liquid column, and bubbling bed technologies [5-8]. This paper proposes the pressurized liquid-screen bed, which increases gas-phase operating pressure to raise gas mass flow rate, thereby increasing gas-liquid contact and improving 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 study how differential pressure, its pulsation, and resistance coefficients influence gas-liquid interaction, this paper establishes a pressure monitoring experimental platform for pressurized liquid-screen beds to investigate these relationships by controlling and varying gas-liquid flow rates and operating pressures. The experimental data and theoretical analysis provide a theoretical basis for enhancing 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 [Figure 1: see original paper]. The platform consists of an upper absorption section and a lower mixing section. In the ab-

sorption section, circulating slurry contacts flue gas thoroughly, while in the mixing section, the slurry after gas-liquid interaction mixes with fresh slurry. A counter-current absorption tower was selected, where gas flow direction opposes liquid descent direction. To facilitate observation of the liquid-screen flow state, the tower body was constructed using an 11 mm thick, 110 mm diameter acrylic pipe with a height of 1000 mm and an internal circular channel cross-section of 88 mm diameter. Slurry nozzles are arranged at the lower part of the absorption tower. The nozzle array uses a divergent equidistant arrangement. This paper employs a 2×8 nozzle configuration with 16 nozzles, as shown in Figure 2 [Figure 2: see original paper].

The liquid-phase circulation system supplies and recycles the absorption liquid. Water was used to simulate slurry in this study. The system primarily comprises a slurry tank, circulation pump, valves, and an electromagnetic flow meter. The liquid flow rate was measured using an LD-15/Y/ZA/AC/If/N/T2/PTFE/316L electromagnetic flow meter with a range of $0.2 \text{ m}^3 \cdot \text{h}^{-1}$ to $6.0 \text{ m}^3 \cdot \text{h}^{-1}$ and accuracy class 1.

The flue gas system supplies simulated flue gas and exhausts gas after gas-liquid contact to the atmosphere. Air was used to simulate flue gas. The system mainly consists of an air compressor, control valves, flue ducts, and a gas turbine flow meter. Gas flow rate was measured using an LWQ-40E gas turbine flow meter with a range of $3 \text{ m}^3 \cdot \text{h}^{-1}$ to $60 \text{ m}^3 \cdot \text{h}^{-1}$ and accuracy class 1.5.

The differential pressure measurement system employs a CYB21 micro-differential pressure transmitter from Xi'an Ximin 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 16-bit resolution.

This study selected the 2×8 nozzle configuration 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, making it difficult to maintain identical liquid flow rates for investigation, 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 $-\infty < x < \infty$, $f(x) \geq 0$, the approximate value of $\int f(x) dx$ can be obtained using:

$$f(x)dx \approx \frac{n_i}{N\Delta x}$$

where Δx is the class width, P is the probability of group i , n is the frequency of sample point x , and N is the total number of sample points in the population.

For steady flow, when fluctuation signals are sampled over a sufficiently long time period, the resulting probability density function becomes time-independent [11].

This paper describes the flow pulsation in the pressurized liquid-screen bed gas-liquid two-phase flow using five parameters: differential pressure pulsation range, differential pressure pulsation mean, differential pressure pulsation peak, differential pressure pulsation uniformity, and resistance coefficient. The differential pressure distribution range $l\Delta P$ is defined as the range of gas-phase differential pressure in the absorption tower. The differential pressure pulsation mean ΔP_a is defined as the average of all pressure data values collected per unit time. The pulsation peak pressure ΔP_p is defined as the pressure value corresponding to the PDF peak of the gas-phase differential pressure.

3 Theoretical Model Analysis

As shown in Figure 3 [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, E). These regions are not absolute spatial positions but depend on liquid particle velocity v , gas absolute velocity vg , gas-liquid relative velocity, terminal settling velocity sz , and liquid particle diameter d . Region A is where $v > vg$; Region B where $vg > v$; Region C where liquid particles accelerate downward, significantly influenced by d (larger particles have broader Region C coverage); Region D where particles detach from the bed layer due to self-pulsation and gas-phase action; and Region E where particles reach terminal settling velocity sz and move uniformly.

Injected liquid flows co-directionally with gas before reaching the apex, then flows counter-directionally after reaching the vertex. During ascent, when liquid particle velocity v is high (Region A in Figure 3 [Figure 3: see original paper]), liquid accelerates gas flow, reducing gas-phase differential pressure in the experimental section. When v is low (Region B), liquid hinders gas flow, increasing differential pressure. During descent (Region C), the hindering effect of droplets that have not reached the limiting diameter increases with falling distance. In Regions D and E, the hindering effect on gas flow no longer increases.

When gas-phase pressure increases, gas mass flow rate W , density ρ , and kinematic viscosity coefficient ν all increase. Consequently, gas kinetic energy and

momentum increase, enhancing impact and entrainment effects on liquid. Simultaneously, liquid buoyancy f_b in the absorption section increases, terminal settling velocity sz decreases, limiting diameter dz increases, and small-diameter liquid combination is promoted. More liquid particles thus combine into larger droplets after entering Region D, improving gas-liquid contact quantity and duration. These combined effects increase gas-phase differential pressure and its pulsation intensity.

4.1.1 Pressure Pulse Analysis

The gas-phase differential pressure pulsation in the pressurized liquid-screen bed absorption section is influenced by both gas and liquid phases. Pressure pulsation from liquid injection directly results from gas-liquid interaction, while pulsation from gas-phase motion can also enhance gas-liquid contact and mixing. Since data acquisition used equal sampling counts per unit time, each PDF analysis contained the same number of data points. Therefore, the differential pressure pulsation range $l\Delta P$ can represent the possible pressure value coverage under current operating conditions, while PDF indicates the concentration degree of pressure distribution. These two parameters reflect pressure pulsation intensity, which is positively correlated with $l\Delta P$ and negatively correlated with PDF.

Data from the sixth region of selected operating conditions were analyzed. Figure 4 shows the pressure drop PDF analysis results for different gas flow velocities at constant gas-phase pressure ($P = 0.1$ MPa). Figure 5 presents the pressure drop PDF analysis for different liquid jet velocities at constant gas-phase pressure ($P = 0.3$ MPa) and gas velocity ($v_g = 1.80$ m \cdot s⁻¹). Figure 6 [Figure 6: see original paper] shows the pressure drop PDF analysis for different gas-phase pressures at constant gas velocity ($v_g = 1.80$ m \cdot s⁻¹) and liquid jet velocity (data from the sixth region). Figure 7 [Figure 7: see original paper] illustrates the variation of differential pressure pulsation range $l\Delta P$ with liquid jet velocity under different gas-phase pressures.

The following patterns were observed:

1. **Gas velocity effect:** At low gas velocities, PDF is high, ΔP_p is low, and $l\Delta P$ is small, indicating weak pressure pulsation intensity. As v_g increases, the PDF curve shifts rightward, PDF decreases, ΔP_p increases significantly, $l\Delta P$ expands, and pressure pulsation intensity becomes positively correlated with gas velocity.
2. **Liquid jet velocity effect:** With increasing liquid jet velocity, the PDF curve shifts slightly rightward while maintaining stable shape, ΔP_p increases, but other pulsation intensity parameters remain essentially stable. Pressure pulsation intensity is almost unaffected by liquid jet velocity.
3. **Gas-phase pressure effect:** At low gas-phase pressures, PDF is high,

ΔP_p is low, and $l\Delta P$ is small. As gas-phase pressure increases, PDF decreases, pulsation peak pressure increases slightly, differential pressure pulsation range rises substantially, and its fluctuation intensifies. Pressure pulsation intensity is positively correlated with gas-phase pressure.

4.1.2 Pressure Pulse Mean Analysis

Figure 8(a) shows the relationship between differential pressure pulsation mean ΔP_a and liquid jet velocity vl at constant gas velocity but different gas-phase pressures. ΔP_a first increases then decreases with increasing vl , and the inflection point occurs at lower jet velocities when gas velocity is lower. The experimental section differential pressure increases significantly with higher gas-phase pressure.

Figure 8(b) presents the relationship between ΔP_a and vl at constant gas-phase pressure but different gas velocities. ΔP_a again shows an initial increase followed by a decrease, with this phenomenon being more pronounced at lower gas velocities and the inflection point shifting to lower jet velocities. The experimental section differential pressure increases markedly with higher gas velocity.

At low vl , only Region B exists during ascent, where liquid hinders gas motion, and most falling particles do not reach terminal settling velocity sz . As vl increases, liquid continues hindering gas during ascent, while the hindering effect from falling droplets increases continuously, causing ΔP_a to rise. When vl increases further, Region A appears while some falling droplets enter Region E and reach sz , slowing the rate of ΔP_a increase until reaching a peak. With continued vl increase, Region A expands further, more falling droplets enter Region E, and ΔP_a consequently decreases. Higher vg raises the vl required for Region A formation and expansion, shifting the inflection point to higher jet velocities. Increased gas-phase pressure facilitates Region A formation and expansion while reducing sz , shifting the inflection point to lower vl and indicating more significant gas-liquid interaction.

4.2 Resistance Coefficient Analysis

The resistance coefficient of the gas-liquid reaction section is a crucial factor affecting flue gas desulfurization efficiency, industrial application design, and economic viability. Strong gas-liquid interaction inevitably increases flue gas flow resistance, which relates to fan efficiency and energy consumption. Analyzing the resistance coefficient provides design basis for industrial desulfurization tower applications and, more importantly, helps identify the optimal balance between improving desulfurization efficiency and 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 ($\text{kg} \cdot \text{m}^{-3}$), and v is gas velocity ($\text{m} \cdot \text{s}^{-1}$).

Figure 9 Figure 9: see original paper shows the relationship between the experimental section resistance coefficient ε and liquid jet velocity v_l at constant gas velocity but different gas-phase pressures. ε first increases then decreases with increasing v_l , and decreases significantly with higher gas-phase pressure. Figure 9(b) presents the relationship between ε and v_l at constant gas-phase pressure but different gas velocities. ε again shows an initial increase followed by a decrease, with the inflection point occurring at lower v_l for lower gas velocities. When $v_l < 2.0 \text{ m} \cdot \text{s}^{-1}$, lower gas velocities correspond to smaller ε values; when $v_l > 2.0 \text{ m} \cdot \text{s}^{-1}$, lower gas velocities correspond to larger ε values. The region near $v_l = 2.0 \text{ m} \cdot \text{s}^{-1}$ represents an intersection point for multiple curves.

The variation of total resistance f on the gas phase directly reflects changes in resistance coefficient ε . At low v_l , Region C appears and expands while Region A is absent, causing liquid-induced resistance f_w to increase continuously. As v_l increases further, Region A appears and expands, Region C continues expanding but at a slower rate, and Region E appears and expands, causing f_w to keep increasing but with decreasing growth rate. When v_l increases to a certain value, Region A continues expanding, Region C stabilizes, and Region E continues expanding, causing f_w to reach a peak and then decrease.

Without liquid injection, the experimental section total resistance f primarily comes from frictional resistance f_L and local resistance f_j , which are determined by the experimental section structure and gas velocity. With constant structure, f_L and f_j are proportional to gas velocity v_g , so lower v_g corresponds to lower experimental section resistance coefficient ε . At low liquid injection velocities, the liquid-gas interaction is weak, and gas flow behavior resembles empty conditions. When v_l approaches $2.0 \text{ m} \cdot \text{s}^{-1}$, liquid hindering effects on gas flow strengthen. Since Region A is absent at this low liquid velocity, Region C significantly affects gas motion, and low-velocity gas with lower kinetic energy is more susceptible to falling liquid effects, causing rapid resistance coefficient growth at low gas velocities. Because Region A appears and expands at lower liquid injection velocities for low gas flow conditions, the v_l corresponding to the ε peak is also lower.

In the right-side region of the ε - v_l curve inflection point in Figure 9, ε drops sharply with increasing v_l , potentially reducing fan energy consumption, but large liquid injection volumes increase pump energy consumption. The mean differential pressure pulsation also decreases sharply with v_l , which is detrimental to gas-liquid interaction. On the left side of the curve, achieving the

corresponding mean differential pressure pulsation requires only small liquid injection velocities. Since Section 4.1.1 concluded that 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

Using the pressurized liquid-screen bed pressure monitoring experimental platform, this paper experimentally investigated the flow pulsation characteristics of gas-liquid two-phase flow in pressurized liquid-screen beds and established a theoretical model combined with experimental data analysis. The following conclusions were obtained:

1. The trajectory of injected droplets in the pressurized liquid-screen bed is divided into five regions, determined by liquid particle velocity v , gas absolute velocity vg , gas-liquid relative velocity, terminal settling velocity sz , and liquid particle diameter d . In Region A, $v > vg$; in Region B, $vg > v$; in Region C, liquid particles accelerate downward, significantly influenced by d ; in Region D, particles detach from the bed layer; and in Region E, particles reach sz and move uniformly.
2. As gas velocity vg increases, the differential pressure pulsation mean ΔP_a and pressure pulsation intensity increase. As gas-phase pressure increases, both ΔP_a and pressure pulsation intensity increase. ΔP_a first increases then decreases with liquid jet velocity v_l , while pressure pulsation intensity is essentially independent of v_l .
3. As gas velocity vg increases, both the mean resistance coefficient and its distribution range decrease. At low gas velocities, increasing gas-phase pressure reduces the mean resistance coefficient but expands its distribution range. At high gas velocities, increasing gas-phase pressure leaves both the mean resistance coefficient and its distribution range essentially stable. The resistance coefficient ε first increases then decreases with liquid jet 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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