Flow Characteristics in a Jetting Fluidized Bed with Acoustic Assistance

Qingjie Guo,* Chongdian Si, and Jian Zhang
College of Chemical Engineering, Qingdao University of Science and Technology, Qingdao 266042, China

A jetting fluidized bed with acoustic assistance was employed to investigate the jet penetration depth and particle concentration profiles using an optical fiber probe. One type of FCC and two types of quartz sand particles were used as bed materials in this study. Experimental results indicated that the jet penetration depth is increased with increasing fluidizing number, jet nozzle diameter, and jet gas velocity, respectively. The jet penetration depth is decreased with an increase in particle diameter and in particle density. The semitheoretical correlations were developed to predict the jet penetration depth with and without the sound assistance. In the bubbling region, particle concentration increased with an increase in sound pressure level, which had a maximal value at a sound frequency of 150 Hz. The sound excitation had a slight influence on the particle concentration profiles in the jetting region and dense-phase particle compression region.

1. Introduction

The jetting fluidized bed (JFB) is widely applied in the chemical industry, energy, environment, and petroleum industry due to its good mixing behavior, high transfer rate, and fast chemical reaction.1,2 An understanding of the hydrodynamics for a jetting fluidized bed can aid the researchers and engineers in chemical engineering to perform reactor design and process optimization.

The flow characteristics of a jetting fluidized bed with horizontal jet has been extensively investigated3–7 in past decades. When gas is injected into the fluidized bed from a horizontal nozzle, a chain of bubbles or a permanent jet plume with bubbles occurs in the bed, which mainly depends on the material properties, bed configuration, and operating conditions. Chen et al.8 studied the effect of solid concentration on the secondary air jet penetration in a bubbling fluidized bed by a new solid concentration measuring probe. In 1993, Chen and Weinstein9 explored the shape and extent of the void area formed by a horizontal jet in a rectangular fluidized bed using an X-ray system. Their experimental observations revealed that the horizontal jet yielded three regions in the fluidized bed: a coherent void, bubble trains, and a surrounding compaction zone. Furthermore, Hong et al.10 investigated the inclined jet penetration depth in a jet fluidized bed using a video camera and obtained a semitheoretical expression of jet penetration depth. Recently, Guo et al.11 presented the invention about jetting fluidized bed with a partitioned distributor and double horizontal nozzles. Generally, the jet penetration depth and particle concentration were two of the most important parameters to describe the jetting fluidized bed. Up to now, several correlations were developed for predicting the jet penetration depth for horizontal jet on the basis of theoretical analysis and experimental data.10,12–15

With respect to an acoustic fluidized bed, previous articles16–21 reported that an acoustic field can improve the fluidization quality in the fluidized bed. Morse16 investigated the fluidization behavior of fine particles in an acoustic field and found that, in the sound frequency range of 50–400 Hz and at a sound pressure level (SPL) higher than 110 dB, the channeling and slugging for fine particle fluidization can be suppressed significantly. The results of Chironne et al.17 showed that a high-intensity sound could suppress the elutriation of fine particles significantly. In our previous work,20 we draw the conclusion that, for a given sound pressure level and bed weight, the minimum fluidization velocity was significantly reduced and elutriation of nanoparticle agglomerates was much diminished in a large fluidized bed. As an intensification technology, a jetting fluidized bed with sound excitation is developed in the present study. However, no papers have been published on flow characteristics in the jetting fluidized bed with sound assistance. The flow characteristics in a jetting fluidized bed with sound assistance (termed as sound JFB) present a challenge to fluidization engineering. In the present investigation, both jet penetration depth and instantaneous local particle concentration were measured using an optic fiber probe system in a jetting fluidized bed with sound assistance.

2. Experimental Section

2.1. Apparatus. The schematic diagram of the experimental apparatus has been depicted in Figure 1. The experimental apparatus consists of a 1600 mm high Plexiglas fluidized bed with 140 mm i.d. and the assistant equipment. A horizontal nozzle was located at 50 mm above the gas distributor, fixed at the wall of the fluidized bed. The distributor was a porous glass plate with a thickness of 2 mm and the perforated size of 1

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* To whom correspondence should be addressed.
mm. Air was used as the fluidization gas and jet gas, which was supplied by a compressor. Experiments were carried out at ambient conditions. Table 1 listed the physical properties of particles. The static bed heights were kept at 165, 180, and 180 mm using FCC particles, quartz sand no. 1, and quartz sand no. 2 as experimental materials, respectively.

2.2. Measurement Techniques. The gas flow rate was measured by flow meter. For all kinds of flow meters, the accuracy can reach 0.1 m³/h with the accuracy of 5% full scale. A WY32003 signal generator produces electric pulses with various waveforms, such as sine wave, triangle wave, etc. The electric signal was amplified using a sound amplifier and then sent to a 160 mm loudspeaker installed at the top of the fluidized bed. A precision sound pressure level meter (CENTER, Type 320) was employed to measure the sound pressure level in the fluidized bed, with a 130 dB maximum sound pressure level. During the measurements, the sound pressure level meter was calibrated with its precision less than 0.5%. A manometer was installed to measure the pressure drop across the bed.

The jet penetration depth and local particle concentration in an acoustic jetting fluidized bed were measured using an optical fiber system, PV-6A particles velocity measurer, produced by the Institute of Process Engineering of the Chinese Academy of Science. The optical fiber probe was 2.16 mm in outer diameter composed of two bundles of fibers, light-emitting and light-receiving fibers. The received light reflected by the particles is multiplied and converted into a voltage signal by the photomultiplier, a high percentage of the emitted light is reflected back to the probe and the photocell responds with a high voltage signal. For example, when a gas void passes through the probe, relatively little light is reflected back to the probe and the photocell responds by giving a low voltage signal. The voltage signal was further amplified and fed into a PC. For all measurements, the sampling time remained at 60 s at a frequency of 31.25 kHz. A quantitative measure of the local solid concentrations was achieved with prior calibration. In this study, an interior subtraction method was used, the high voltage adjustment in the full scale of the bed and a zero voltage potentiometer which adjusted the output signal to zero when no powder is on the end facet of the probe. Therefore, a direct and fast method for calculating particles concentration by two-point nonuniformity correction is proposed in the dense-phase zone of fluidized bed. To compare calibration precision, the PC-6 fiber optic probe system is also calibrated in a 40 mm i.d. liquid–solid fluidized bed.

For convenience, the origin, (0, 0), corresponds to the center of the jet nozzle position. Axial particle concentration at heights of 10, 50, 90, and 130 mm above the distributor plate were measured by an optical fiber system. To define the horizontal penetration depth, nine horizontal positions represented by radial ratios of radial distance to radius, −0.75, −0.5, −0.25, 0, 0.25, 0.5, 0.75, and 1, were used to measure the local particle concentration.

3. Results and Discussion

3.1. Jet Penetration Depth. The typical jet penetration depth definition was described in Figure 2A, indicating that a large bubble was formed when gas was injected into the bed horizontally. To measure the jet penetration depth, the boundary of the jetting region and bubbling region was defined at a voidage of 0.8, which was adopted by Hong et al. As can be observed from Figure 2B, the horizontal jet penetration depth Lj was defined as the maximum length from the farthest point of the jet to the nozzle when the jet detached from the nozzle. For the horizontal jet, three regions were determined in the jetting fluidized bed using an optical fiber probe: a jetting region (a, ej ≤ 0.28), a bubbling region (b, 0.28 < ej ≤ 0.44), and a dense-phase particle compression region (c, ej ≥ 0.44), as depicted in Figure 3. The preceding conclusions were consistent with the findings of Chen and Weinstein, who used an X-ray system to define three regions in a fluidized bed with a horizontal jet, i.e., a coherent void, bubble trains, and a surrounding compaction zone.

The region above the horizontal nozzle within the jet penetration depth was defined as a jetting region, while the region above the horizontal nozzle due to the jet gas and fluidization gas being collapsed into bubbles is defined as a bubbling region and the region nearby the fluidized bed wall refers to a dense-phase particle compression region.

Table 1. Physical Properties of Particles

<table>
<thead>
<tr>
<th>bed material</th>
<th>particle diameter /μm</th>
<th>particle density/(kg·m⁻³)</th>
<th>bulk voidage</th>
<th>min fluidization velocity/(m·s⁻¹)</th>
<th>Geldart type</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC</td>
<td>85</td>
<td>1807.5</td>
<td>0.434</td>
<td>0.0043</td>
<td>A</td>
</tr>
<tr>
<td>quartz sand, no. 1</td>
<td>85</td>
<td>2650</td>
<td>0.457</td>
<td>0.0064</td>
<td>A</td>
</tr>
<tr>
<td>quartz sand, no. 2</td>
<td>115</td>
<td>2650</td>
<td>0.471</td>
<td>0.0117</td>
<td>B</td>
</tr>
</tbody>
</table>

Figure 2. Definition of the horizontal jet penetration depth, Lj.
jet gas velocity. This conclusion was consistent with the findings of other researchers.\textsuperscript{12–15} As shown in Figure 4, the different investigators employed various fluidized beds with different dimensions, different nozzles with varied inside diameters, different bed materials, and jet velocity. Accordingly, previous papers developed different correlations. The differences of various correlations are attributed to the various definitions of penetration depth and experimental conditions. Therefore, the different correlations obtain different penetration depth at the same jet velocity.

3.1.2. Effect of Jet Nozzle Diameter on Jet Penetration Depth. The effect of jet nozzle diameter on jet penetration depth is described in Figure 5. At a given jet gas velocity, the jet penetration depth is increased with increasing jet nozzle diameter. The variation in the trends results from the fact that increasing nozzle diameter caused the greater jet momentum because the jet momentum at the nozzle exit is proportional to the dimension of the jet nozzle diameter. Also, Merry,\textsuperscript{12} Benjelloun et al.,\textsuperscript{15} and Hong et al.\textsuperscript{10} demonstrated that the jet penetration depth is increased with increasing jet nozzle diameter.

3.1.3. Effect of Fluidizing Number on Jet Penetration Depth. Figure 6 illustrates the effect of fluidizing number ($u_j/\bar{u}_{mf}$) on the jet penetration depth. As superficial velocity exceeds the minimum fluidization velocity, bubbles are generated in the distributor, and bubbles coalesced while bubbles ascended in the bed. As expected, bubble coalescence causes gas and air mixing. With increasing $u_j/\bar{u}_{mf}$, the number and the size of the bubbles increase, enhancing mixing between the jet gas and fluidization gas. Consequently, the jet penetration depth increased with increasing $u_j/\bar{u}_{mf}$. Furthermore, as observed in Figure 6, the penetration depth in the jetting fluidized bed with sound assistance is greater than that in the jetting fluidized bed. The sound energy can break up larger bubbles into small ones for FCC particles in an acoustic fluidized bed. At a given sound frequency, the sound energy is proportional to the sound pressure level. As the sound pressure level rises, the increased sound energy disrupts large bubbles into many small ones, which causes increased solid concentration. Therefore, the jet momentum dissipation loss is reduced greatly. For this reason, the jet penetration depths in jetting fluidized beds with sound assistance are greater than those in jetting fluidized beds.

3.1.4. Effects of Particle Physical Properties on the Jet Penetration Depth. Figure 7 depicts that the influence of particle density and particle diameter on the jet penetration depth. It has been found that the jet penetration depth decreases with increasing particle density and particle diameter at the same jet gas velocity. The jet drag force between jet gas and solid particle increased with increasing particle density and particle diameter. The jet momentum was consumed due to increased jet drag force, which caused a decrease in jet penetration depth. Figure 7 indicated that high-intensity sound waves results in increased jet penetration depth. The reason is that the increased sound energy disrupts large bubbles into many small ones, which causes increased solid concentration and reduced momentum dissipation loss.

3.1.5. Effect of Sound Frequency on the Jet Penetration Depth. To examine the effect of the sound frequency on the jet penetration depth, a series of experiments were performed at the sound frequency varying from 50 to 400 Hz and sound diameter.
pressure level ranging from 90 to 120 dB. When the sound pressure level was kept constant, the jet penetration depth increased with increasing sound frequency, ranging from 50 to 150 Hz, and then further decreased with increasing the sound frequency varying from 150 to 400 Hz, as illustrated in Figure 8. In terms of Stokes–Kerchief’s formula,\(^1^8\) sound absorption coefficient was inverse proportional to the square of the sound frequency, which was represented by the expression:

\[
A_s = \frac{\alpha f}{\rho c^2} = \frac{8\pi^2 \eta'}{3\rho c^2} + \frac{2\pi^2}{\rho c^2} \left[ \frac{1}{C_v} - \frac{1}{C_p} \right] = A_{\eta'} + A_{\eta} \tag{1}
\]

where \(A_s\) is constant; this equation was described by two main variables: normalized viscosity (\(A_{\eta'}\)) and normalized thermal conductivity (\(A_{\eta}\)). The sound coefficient increased with an increase in sound frequency, and the sound energy was attenuated greatly when the sound frequency exceeded 150 Hz. On the other hand, the effect of the acoustic field on the jet penetration depth was weakened and even disappeared when the jet velocity was lower than 47.2 m/s. This was due to the fact that the sound energy was attenuated greatly as the sound waves propagated through the bubbling region and dense-phase particle compression region. On the basis of the above discussion, the sound wave at 150 Hz has relative great energy which compresses the dense-phase region. It is concluded that there exists relative minimum jet momentum dissipation at a sound frequency of 150 Hz.

The influence of sound frequency on the particle concentration profiles is shown in Figure 9. It shows that the particle concentration remained constant (around 0.11 and 0.44) in the jetting region and the dense-phase particle compression region, respectively. In the case of the greater jet momentum in the jetting region, the effect of sound frequency on the particle concentration is weakened, and even disappeared. In a dense-phase particle compression region, most of the sound waves energy was attenuated greatly as the sound waves propagated through the dense-phase particle compression region. The sound frequency imposed more influence on the particle concentration in the bubbling region than in other regions. As described in Figure 9, that particle concentration increased with increasing sound frequency varying from 50 to 150 Hz and then further decreased with increasing sound frequency, varying from 150 to 400 Hz in the bubbling region. This can be explained as follows: (1) the vibration cycle of low frequency sound waves were too long to excite the particle concentration profiles continuously; (2) an increase in sound frequency caused increasing sound coefficient, and the effect of sound waves energy on the particle concentration was weakened, and even disappeared.

The influence of sound frequency on the axial profiles of particle concentration is displayed in Figure 10, which demonstrates that the axial particle concentration profile is a strong function of bed height. The lowest particle concentration was always at the lowest axial level (\(H = 10\) mm) belonging to the jetting region. With increasing axial height, the particle concentration decreased at different sound frequencies in the bubbling region. At all axial heights, the particle concentration had its maximum value at \(f = 150\) Hz and decreased at low frequency (0−150 Hz) and high frequency (150−400 Hz). This axial nonmonotonic particle distribution was in agreement with
the results reported by Si and Guo\textsuperscript{21} which demonstrates that jet momentum dissipation has a minimum value at 150 Hz.

### 3.1.6. Effect of Sound Pressure Level on the Jet Penetration Depth

In view of early discussions, the sound frequency was kept at 150 Hz in the following experiments. The sound pressure levels, from 90 to 120 dB, were used to explore the influence of the sound pressure level on the jet penetration depth. It can be observed from Figure 11 that the jet penetration depth increased with an increase in sound pressure level at the same sound frequency. Guo’s sound energy model\textsuperscript{4} demonstrated that sound energy increased with increasing sound pressure level, which was represented by the expression

$$E_{sou} = \frac{1}{4} \pi d_p^2 I = \frac{1}{4} \pi d_p^2 \kappa_s (10^{-12+SPL}) (\frac{f}{f_c})^n (SPL-SPL_c/SPL_c)$$

(2)

By eq 2, the sound waves with a high sound pressure level had relatively greater energy which improved the fluidization quality. The increased sound energy disrupts large bubbles into much more small ones, which causes great solid concentration. Therefore, the jet momentum dissipation loss is reduced greatly. Consequently, the jet penetration depth increased significantly by sound wave excitation.

The influence of sound pressure level on the particle concentration profiles is displayed in Figure 12. It indicates that the particle concentration remains constant (around 0.12 and 0.44) in the jetting region and dense-phase particle compression region, respectively. The sound pressure level had little effect on the particle concentration in the jetting region and dense-phase particle compression region. In addition, the particle concentration increased with increasing sound pressure level in the bubbling region. Consequently, sound waves with high sound pressure level had greater energy which disrupted effectively the bubble.

The influence of sound pressure level on the radial profiles of particle concentration has been illuminated in Figure 13. With increasing sound pressure level, the particle concentration increased dramatically. However, this increasing trend became slight in the jetting region, where the particles concentration almost maintained constant at the sound pressure level range from 90 to 120 dB.

### 3.2. Jet Penetration Depth Correlation

#### 3.2.1. New Jet Penetration Depth Correlation without Sound Action

The existing correlations for horizontal gas jet penetration depth in the literature have been summarized in Table 2. Different definitions of jet penetration depth were used in such correlations. The maximum jet penetration depth was generally adopted, in which the mean value of the maximum and minimum penetration length was adopted. It has been demonstrated that jet gas velocity, jet nozzle diameter, particle density, particle diameter, and fluidizing gas density have influence on the jet penetration depth. However, the effect of superficial gas velocity ($u/u_{mf}$) on the penetration depth fails to be investigated for all of the above correlations.

The jet momentum, the drag between two phases, and the particle entrainment determine the dimensionless jet penetration depth ($L_j/D_j$). Therefore, we select the dimensionless fluidizing number ($u/u_{mf}$); the Froude number ($Fr^*$), which described the inertia of gas jet; and the Reynolds number ($Re$), which is the ratio of inertia force to viscous force. $Re$ is the criterion for the drag and entrainment, too. The effect of the ratio of gas to solid density on jet penetration depth is also included in $Fr^*$. By correlating all experimental data in this study, the following correlation was proposed for estimating the jet penetration depth.

$$\frac{L_j}{D_j} = 0.457 \left( \frac{u}{u_{mf}} \right)^{1.794} Re^{0.559} (Fr^*)^{0.125}$$

(3)

10 m/s $\leq u_j \leq 140$ m/s, $1 \leq \frac{u}{u_{mf}} < 2.0$

where

$$Fr^* = \frac{\rho_j u_j^2}{(\rho_p - \rho_j) g D_j}$$

(4)

$$Re = \frac{\rho_j u_j D_j}{\mu}$$

(5)

The comparison of all experimental data for jet penetration depth with the correlation eq 3 and other published data have
been drawn in Figure 14. Because other correlations\textsuperscript{12,15} hardly consider the effect of the dimensionless fluidizing number ($u/u_{mf}$) on the jet penetration depth, there were large relative errors between the experimental data and the calculated results, and the maximum error of eq 3 was below 20%.

3.2.2. New Jet Penetration Depth Correlation with Acoustic Excitation. According to the present discussion, the high-intensity sound waves result in a decrease of the jet penetration depth. Consequently, eq 3 needs to be modified for prediction of jet penetration depth; there existed large relative errors between the experimental data and the calculated results. The jet penetration depth was a function of the sound frequency and sound pressure level, besides the above factors. Guo et al.\textsuperscript{4} presented that the sound waves coefficient ($k$) is a function of the dimensionless sound frequency ratio and sound pressure level ratio; that is,

$$k = \frac{f}{f_c} \left( \frac{SPL - SPL_c}{SPL_c} \right)$$

where $f_c = 150$ Hz and $SPL_c = 100$ dB are the critical sound frequency and critical sound pressure level in this study, respectively. $f$ represented the sound frequency, and SPL denoted the sound pressure level. The new correlation is derived from the following dimensionless form to predict the jet penetration depth at different sound wave parameters in an acoustic jetting fluidized bed.

$$\left( \frac{L_j}{D_j} \right)_{sou} = \frac{u}{u_{mf}} \cdot Fr^* \cdot Re \cdot \left( \frac{f}{f_c} \right) \left( \frac{SPL - SPL_c}{SPL_c} \right)$$

$$1 \leq \frac{u}{u_{mf}} < 2.0, \quad \frac{1}{3} \leq \frac{f}{f_c} \leq \frac{8}{3}, \quad \text{and} \quad -0.25 \leq \frac{SPL - SPL_c}{SPL_c} \leq 0$$

A new empirical correlation to predict the jet penetration depth in an acoustic jetting fluidized bed was developed using the multiple linear regression method, given by

$$\left( \frac{L_j}{D_j} \right)_{sou} = 0.5444 \left( \frac{u}{u_{mf}} \right)^{1.1363} \cdot Re^{0.451} (Fr^*)^{0.261} \cdot \left( \frac{f}{f_c} \right)^{-0.061} \cdot e^{0.169(SPL - SPL_c) / SPL_c}$$

Table 2. Correlations for Horizontal Jet Penetration Length in Literature

<table>
<thead>
<tr>
<th>ref</th>
<th>fluidized bed</th>
<th>nozzle diam</th>
<th>bed materials</th>
<th>jet velocity</th>
<th>correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hong et al.\textsuperscript{10}</td>
<td>two-dimensional</td>
<td>0.18-1.5 mm</td>
<td>millet, millet</td>
<td>26.2-218 m/s</td>
<td>$L = 3.8 + 4.5 = 5.25 \left( \frac{u}{u_{mf}} \right)^{0.45} \left( \frac{Fr^*}{Fr_c} \right)^{0.5} \left( \frac{Re}{Re_c} \right)^{0.3} \left( \frac{f}{f_c} \right)^{0.2}$</td>
</tr>
<tr>
<td>Merry\textsuperscript{12}</td>
<td>two-dimensional</td>
<td>1.0-1.5 mm</td>
<td>sand, steel shot, kale seeds</td>
<td>50-300 m/s</td>
<td>$L = 3.2799 + 1.57 \left( \frac{u}{u_{mf}} \right)^{0.4} \left( \frac{Fr^*}{Fr_c} \right)^{0.5} \left( \frac{Re}{Re_c} \right)^{0.3} \left( \frac{f}{f_c} \right)^{0.2}$</td>
</tr>
<tr>
<td>Shakhova\textsuperscript{13}</td>
<td>three-dimensional</td>
<td>4 mm</td>
<td>copolymer</td>
<td>10.3-40.8 m/s</td>
<td>$L = 0.044 \left( \frac{u}{u_{mf}} \right)^{0.4} \left( \frac{Fr^*}{Fr_c} \right)^{0.5} \left( \frac{Re}{Re_c} \right)^{0.3} \left( \frac{f}{f_c} \right)^{0.2}$</td>
</tr>
<tr>
<td>Zhou and Shen\textsuperscript{6}</td>
<td>two-dimensional</td>
<td>7.9 mm, 14 mm id.; circular</td>
<td>2.8-118 m/s</td>
<td>$L = 0.044 \left( \frac{u}{u_{mf}} \right)^{0.4} \left( \frac{Fr^*}{Fr_c} \right)^{0.5} \left( \frac{Re}{Re_c} \right)^{0.3} \left( \frac{f}{f_c} \right)^{0.2}$</td>
<td></td>
</tr>
<tr>
<td>Zenz\textsuperscript{14}</td>
<td>two-dimensional</td>
<td>0.05-2 mm sand</td>
<td>4 mm</td>
<td>$L = 0.044 \left( \frac{u}{u_{mf}} \right)^{0.4} \left( \frac{Fr^*}{Fr_c} \right)^{0.5} \left( \frac{Re}{Re_c} \right)^{0.3} \left( \frac{f}{f_c} \right)^{0.2}$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 14. Comparison between predicted data of jet penetration depth and experimental data.
10 m/s ≤ \( u_j \) ≤ 140 m/s, \( 1 \leq \frac{u}{u_{mf}} < 2.0 \), 50 Hz ≤ \( f \) ≤ 400 Hz, and 90 dB ≤ SPL ≤ 120 dB.

The comparison of all experimental data for the jet penetration depth with the correlation eq 3 and eq 8 was illustrated in Figure 15. It can be found that the calculated values predicted by eq 3 were smaller than experimental data. By contrast, eq 8 was in good agreement with the experimental data in jetting fluidized bed with sound assistance with a deviation within 25%.

4. Conclusions

From the present investigation, the conclusions can be drawn as follows:

(1) The jet penetration depth increased with an increase in the jetting velocity. At the same jet gas velocity, the penetration depth increased as the nozzle diameter and fluidizing number increased. The jet penetration depth increased with an increase in sound pressure level at the same sound frequency. When the sound pressure level was fixed, the jet penetration depth increased with increasing sound frequency varying from 50 to 150 Hz and then further decreased with increasing sound frequency varying from 150 to 400 Hz.

(2) A new correlation for jet penetration depth in an acoustic jetting fluidized bed was also proposed.

\[
\frac{L_j}{D_j} = 0.5444 \left( \frac{u}{u_{mf}} \right)^{1.636} Re^{0.454} (Fr^*)^{0.261} \left( \frac{F}{f_c} \right)^{-0.061} \left( \frac{SPL}{SPL_c} \right)^{0.169} \]

(3) The particle concentration increased with the increasing distance away from the jet nozzle. In the bubbling region, particle concentration decreased with an increasing of jet nozzle diameter, fluidizing number, and jet gas velocity. The particle concentration remained constant in the jetting region and dense-phase particle compression region, respectively.

(4) The effect of sound waves on the particle concentration was weakened and even disappeared in the jetting region and dense-phase particle compression region. In the bubbling region, the particle concentration increased with an increase in sound pressure level at the same sound frequency. When the sound pressure level was fixed, the particle concentration increased with increasing sound frequency varying from 50 to 150 Hz and then further decreased with increasing sound frequency varying from 150 to 400 Hz.

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Nomenclature

\( d_p \) = particle diameter (m)  
\( D_j \) = nozzle diameter (m)  
\( E_{sou} \) = sound energy (J)  
\( f \) = sound frequency (Hz)  
\( f_c \) = transitional sound frequency (Hz)  
\( Fr^* \) = two-phase Froude number  
\( g \) = gravitational constant (m/s²)  
\( H \) = axial height (m)  
\( k_s \) = sound energy constant  
\( L_j \) = jet penetration depth (m)  
\( r \) = radial length (m)  
\( R \) = jetting fluidized-bed radius (m)  
\( Re \) = Reynolds number  
\( R_{eq} \) = particle Reynolds number  
\( SPL \) = sound pressure level (dB)  
\( SPL_c \) = transitional sound pressure level (dB)  
\( t \) = time (s)  
\( u \) = total superficial gas velocity (m/s)  
\( u_j \) = nozzle jetting gas velocity (m/s)  
\( u_{suf} \) = superficial gas velocity through one nozzle (m/s)  
\( u_{mf} \) = minimum fluidization velocity (m/s)  
\( Z \) = distance from the jet nozzle (mm)

Greek Letters

\( \varepsilon \) = particle concentration  
\( \mu \) = air viscosity (Pa·s)  
\( \rho_p \) = particle density (kg·m⁻³)  
\( \rho_i \) = air density (kg·m⁻³)

Literature Cited


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