7-2012

Acoustic Field Effects on Minimum Fluidization Velocity in a 3D Fluidized Bed

David R. Escudero
Iowa State University, drescude@iastate.edu

Theodore J. Heindel
Iowa State University, theindel@iastate.edu

Acoustic Field Effects on Minimum Fluidization Velocity in a 3D Fluidized Bed

Abstract

Fluidized beds are used in a variety of process industries because they provide uniform temperature distributions, low pressure drops, and high heat/mass rates. Minimum fluidization velocity is an important factor in understanding the hydrodynamic behavior of fluidized beds, and this characteristic may be modified through high frequency (sound) vibrations. The effects caused by sound wave frequency on the minimum fluidization velocity in a 3D fluidized bed are investigated in this study. Experiments are carried out in a 10.2 cm ID cold flow fluidized bed filled with glass beads with material density of 2600 kg/m^3, and particles sizes ranging between 212–600 μm. In this study, four different bed height-to-diameter ratios are examined: H/D = 0.5, 1, 1.5, and 2. Moreover, the sound frequency of the loudspeaker used as the acoustic source ranges between 50–200 Hz, with a sound pressure level fixed at 110 dB. Results show that the minimum fluidization velocity is influenced by the frequency change. As the frequency increases, the minimum fluidization velocity decreases until a specific frequency is reached, beyond which the minimum fluidization velocity increases. Thus, acoustic fields provide an improvement in the ease of fluidization of these particles.

Keywords

acoustic field, bed height, fluidized bed, minimum fluidization velocity

Disciplines

Acoustics, Dynamics, and Controls | Fluid Dynamics

Comments

This is a conference proceeding from *ASME 2012 Fluids Engineering Division Summer Meeting* 2 (2012): 47, doi:10.1115/FEDSM2012-72041. Posted with permission.

Proceedings of the ASME 2012 Fluids Engineering Summer Meeting
FEDSM2012
July 8-12, 2012, Rio Grande, Puerto Rico

FEDSM2012-72041

ACOUSTIC FIELD EFFECTS ON MINIMUM FLUIDIZATION VELOCITY IN A 3D FLUIDIZED BED

David R. Escudero† **and Theodore J. Heindel**
Department of Mechanical Engineering
Iowa State University
Ames, Iowa 50011

ABSTRACT

Fluidized beds are used in a variety of process industries because they provide uniform temperature distributions, low pressure drops, and high heat/mass rates. Minimum fluidization velocity is an important factor in understanding the hydrodynamic behavior of fluidized beds, and this characteristic may be modified through high frequency (sound) vibrations. The effects caused by sound wave frequency on the minimum fluidization velocity in a 3D fluidized bed are investigated in this study. Experiments are carried out in a 10.2 cm ID cold flow fluidized bed filled with glass beads with material density of 2600 kg/m^3, and particles sizes ranging between 212-600 μm. In this study, four different bed height-to-diameter ratios are examined: H/D = 0.5, 1, 1.5, and 2. Moreover, the sound frequency of the loudspeaker used as the acoustic source ranges between 50-200 Hz, with a sound pressure level fixed at 110 dB. Results show that the minimum fluidization velocity is influenced by the frequency change. As the frequency increases, the minimum fluidization velocity decreases until a specific frequency is reached, beyond which the minimum fluidization velocity increases. Thus, acoustic fields provide an improvement in the ease of fluidization of these particles.

Keywords: Acoustic field, bed height, fluidized bed, minimum fluidization velocity.

INTRODUCTION

Fluidized bed hydrodynamic behavior is very complex and must be understood to improve fluidized bed operations. One of the most important parameters to characterize fluidized bed conditions is the minimum fluidization velocity (U_{mf}) [1], which is related to the drag force needed to attain solid suspension in the gas phase. The minimum fluidization velocity also constitutes a reference for evaluating fluidization intensity when the bed is operated at higher gas velocities [2]. In general, U_{mf} is a function of particle properties/geometry, fluid properties, and bed geometry.

Sau et al. [3] determined the minimum fluidization velocity for a gas-solid system in a tapered fluidized bed and studied the effects that bed geometry, specifically the tapered angle, had on the minimum fluidization velocity. They used three different angles (4.61°, 7.47°, and 9.52°) to observe the effect on minimum fluidization velocity. Results showed that as the tapered angle increased, U_{mf} increased, which implied a dependence of the minimum fluidization velocity to the geometry of the fluidized bed. Moreover, Hilal et al. [4] analyzed the effects of bed diameter, gas distributor, and inserts on minimum fluidization velocity. It was shown that both the bed diameter and the type and geometry of the distributor affected U_{mf}. For example, U_{mf} increased with an increase in the number of holes in the distributor plate. Furthermore, with an increase in the bed diameter there was a decrease in U_{mf}. Finally, the insertion of tubes along the fluidized bed reduced the effective cross-sectional area for fluidization, which produced a high interstitial gas velocity causing a decrease in U_{mf}.

The influence of bed height on minimum fluidization velocity has been studied using different types of fluidized beds. Zhong et al. [5] completed minimum fluidization experiments in spouted fluidized beds. In a spouted fluidized bed, the bed chamber is tapered like a funnel, which creates different hydrodynamics, and the fluidization air is typically injected through a single orifice. Zhong et al. [5] used a two dimensional spouted fluidized bed with dimensions 300 mm ×

†Corresponding Author: David Escudero (drescude@iastate.edu)

30 mm and a height of 2000 mm, and fluidized a variety of Geldart Type-D particles (e.g., mung beans, polystyrene, millet). Filling the bed with these materials to different heights (300-550 mm), they determined the minimum spouting fluidization velocity, defined as the minimum superficial gas velocity at which the spout initiates in the central region and the surrounding annulus is fluidized; this is analogous to minimum fluidization velocity in a bubbling fluidized bed. They concluded that the static bed height for a spouted bed influenced the minimum spouting fluidization velocity; increasing the bed height increased the spouting velocity.

Sau et al. [3] used a gas-solid conical tapered fluidized bed to find the minimum fluidization velocity and the pressure drop across the bed. The dimensions of the fluidized bed at the bottom were 48, 42, and 50 mm, the top of the bed measured 132, 174, and 212 mm, and the column heights were 520, 504 and 483 mm, respectively. They concluded that bed height for this type of bed did not have a significant effect on the minimum fluidization velocity, i.e., U_{mf} was independent of bed height for this type of conical tapered fluidized bed.

Ramos et al. [1] studied the minimum fluidization velocity for gas-solid 2D fluidized beds. They used a rectangular bed (1×0.2×0.012 m) filled with glass beads of three different diameters (160-250, 250-400, and 490-700 μm) and various bed heights (2, 4, 8, 16, 20, 40, and 60 cm). Their results revealed that as the static bed height increased, U_{mf} increased.

Gunn and Hilal [6] studied gas-solid fluidized beds using glass beads with beds that had 89 and 290 mm ID. The glass beads diameters were 100 and 500 μm. They used four different bed heights (20, 30, 40, 50 cm). The results for minimum fluidization velocity showed that for all the material and experimental conditions used in this study there was no significant change in the minimum fluidization velocity when the bed height was increased. Therefore, U_{mf} was independent of bed height.

Cranfield and Geldart [7] studied the fluidization characteristics of large particles (1000-2000 μm) of alkalized alumina in a fluidized bed with a cross-sectional area of 61×61 cm at different bed heights (5, 10, 15, 20, 25, and 30 cm). They showed that for 3D beds, the minimum fluidization velocity remained constant no matter the bed height used in the experiments. Similar results showing independence between minimum fluidization velocity and bed height were concluded by Escudero and Heindel [8] using different Geldart type B particles (glass beads, ground walnut shell and ground corncob) in the size range of 500-600 μm.

Sound-assisted fluidized beds have been studied for different Geldart type particles (Geldart type A-C) to understand the effects produced by the acoustic field on the fluidization behavior and quality. This is an attractive option because it is a non-invasive technique that does not change the internal structure of the bed and there is no limitation to the particle type that can be fluidized.

Leu et al. [9] studied the fluidization of Geldart type B particles in an acoustic fluidized bed. They determined the influence of the speaker power, sound frequency, particle loading, and distance between the speaker and bed surface on the hydrodynamic properties of a fluidized bed filled with 194 μm sand. They found that when an acoustic field is applied, a different particle loading height creates a different minimum fluidization velocity, making minimum fluidization velocity dependent on bed height. Finally, they showed that the standard deviation of the pressure fluctuations and the bubble rise velocity was reduced in the presence of an acoustic field.

Guo et al. [10] investigated the behavior of ultrafine (Geldart type C) particles under the influence of sound waves. They studied both nanometer and micrometer size particles. They found that as frequency increased, the minimum fluidization velocity decreased and then after a specified frequency (40-50 Hz), the minimum fluidization velocity increased. When the sound pressure level was changed (100 dB - 103.4 dB) and the sound frequency fixed, the minimum fluidization velocity decreased for all particles, thus improving the fluidization quality of the particles. The same trends were found by Kaliyaperumal et al. [11] and Levy et al. [12].

Moreover, Guo et al. [13] analyzed the effects of the acoustic field on a fluidized bed at different temperatures for quartz sand (74 μm, 2650 kg/m^3) and SiO_2 particles (0.5 μm, 2560 kg/m^3). The results obtained in that study showed that minimum fluidization velocity decreased with increasing temperature with, as well as without, acoustic assistance. In the same way, at a fixed sound pressure level (120 dB), the minimum fluidization velocity decreased when the frequency was increased from 50-200 Hz, and then the minimum fluidization velocity increased with frequency from 200-400 Hz.

Si and Guo [14] studied how an acoustic fluidized bed improved the fluidization of two different biomass particles, sawdust and wheat stalks, alone or mixed with quartz sand. They compared the fluidization behavior of the biomass without and with the acoustic field to determine if there was any improvement due to the acoustic field. Additionally, they determined the effects that the sound pressure level (SPL) had on the minimum fluidization velocity. Initially, they found that the biomass by itself fluidized poorly with and without the presence of the acoustic field. Then, they added quartz sand to aid fluidization and maintained the biomass mass fraction at 60%. They observed that below a SPL of 90 dB, plugging and channeling occurred in the fluidized bed. Increasing the SPL diminished the effects of channeling and improved the quality of fluidization. By varying the sound frequency between 50 to 400 Hz, they determined that the minimum fluidization velocity decreased with increasing frequency until it reached a minimum value and then increased with increasing frequency.

Si and Guo [14] also fixed the sound frequency at 150 Hz and varied the sound pressure level between 90 and 120 dB. Using these conditions, they determined the effects on the minimum fluidization velocity. They found that, when the sound pressure level was above 100 dB, the fluidization quality improved, and they observed that the biomass mixture fluidized smoothly without any obvious slugging or channeling.

The goal of this paper is to determine the effects caused by an acoustic field on the minimum fluidization velocity of a Geldart type B particle in a 3D cylindrical fluidized bed filled to different bed heights.

EXPERIMENTAL SETUP

The reactor used in these experiments is a cold flow fluidized bed reactor. The cylindrical fluidized bed was fabricated with 10.2 cm internal diameter (ID) acrylic with a 0.64 cm wall thickness. As shown in Figure 1, the reactor consists of three main chambers: the top chamber or freeboard region, the bed chamber, and the plenum. Fluidization occurs in the bed chamber which is 30.5 cm tall and 10.2 cm ID. Square flanges (16.5×16.5 cm) connect each section. An aeration plate is located immediately below the bed chamber; it is fabricated from a 1.27 cm thick acrylic plate with 62, 1 mm diameter holes spaced approximately 1.27 cm apart in a circular grid for a total open area of 0.62%.

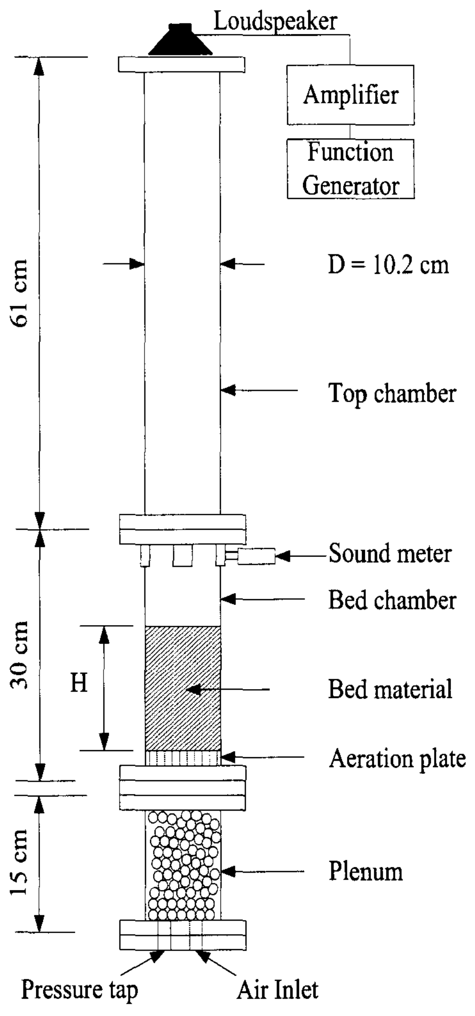

FIGURE 1: FLUIDIZED BED REACTOR (NOT TO SCALE). THE STATIC BED HEIGHT IS IDENTIFIED BY H.

Compressed air from the laboratory's building air supply is used as the fluidizing gas for this research. The pressure at which the compressed air is delivered inside the laboratory is 620 kPa (90 psi). However, since the flow rates used for fluidization vary depending of the specific conditions of each experiment, an air flow control board with four independent air lines is used to deliver the required air to the fluidized bed.

The fluidized bed air flow is regulated via a manual stainless steel pressure regulator and attached filter, with a pressure range of 0-862 kPa (0-125 psi) and maximum inlet pressure of 2.07 MPa (300 psi), and a stepper motor valve Aalborg SMV40-SVF2-A. The regulated air flows through a 0-1000 Lpm stainless steel Aalborg GFM771 flow meter.

Pressure is measured with a Dwyer 0-34.5 kPa (0-5 psig), 4-20 mA output pressure transducer located in the bottom of the plenum. The signals obtained from the pressure transducer and mass flow meter are connected to a computer controlled data acquisition system. Average measurements were necessary due to the highly variable pressure signal caused by the bubbling fluidized bed. In this study, data collection occurred at a rate of 1000 Hz for a time interval of 5 seconds; average pressure and average fluidization gas flow rate were subsequently written to a data file.

The fluidizing material used in this study was glass beads (ρ_{glass} = 2600 kg/m^3) over three different size ranges (212-425 μm, 425-500 μm, and 500-600 μm). The bed bulk density was determined knowing the material mass and the static bed volume. Bed material was slowly added until the desired static bed height was reached, which corresponded to H/D = 0.5, 1, 1.5, and 2. Before the bed height was measured, the bed was fluidized and then allowed to collapse to avoid any packing effects due to the filling process. The material mass was then measured and the given bed bulk density was calculated. Table 1 summarizes the general bed characteristics.

TABLE 1: BED MATERIAL PROPERTIES.

	Glass Beads	
H/D	**Bed Mass (g)**	**Bulk density (kg/m^3)**
0.5	680	1650
1	1300	1580
1.5	1930	1560
2	2570	1560
Diameter (μm)	212-425, 425-500, 500-600	
Particle Density (kg/m^3)	2600	

To avoid electrostatic effects that may build up during fluidization, the fluidization air is passed through a humidifier before entering the fluidized bed inlet. Several trials in the laboratory have shown that using this simple solution minimized electrostatic effects.

The minimum fluidization velocity is defined as the minimum superficial gas velocity where particle fluidization is achieved. Minimum fluidization velocity is determined using the following pressure measurement procedure. First, the reactor is filled with the desired material to a specified height. Air at U_g = 40.8 cm/s is passed through the bed for about an hour to condition the system. After the conditioning period, the pressure and flow rate are acquired using the DAQ system. Data are collected at 1000 Hz over a 5 second interval, averaged over this period, and then output to an Excel file. Next, the air flow rate is decreased by 1 cm/s by automatically closing the stepper motor valve. Then, when the flow rate mean, the pressure mean, and the pressure standard deviation are between specific thresholds, the DAQ system again records the pressure and flow rate and averages them over a 5 second interval. This process is repeated until the flow rate reaches approximately U_g = 0 cm/s; at this point the test is completed. For statistical purposes, each test for every specified condition is repeated 10 times. These tests were carried out without sound, as a reference state, and with sound emitted from a Peerless 7.62 cm ID full range woofer located at the top of the bed. Sine waves at different frequencies (50-200 Hz) are generated by a function generator and passed through an amplifier (Audio Source AMP100); the sound pressure level is fixed at 110 dB and is read by a sound meter located above the bed chamber.

After all the bed material data are collected, the same procedure is repeated in an empty reactor. This is done to quantify the pressure drop through the aeration plate and plenum. The empty reactor pressure data are then subtracted from the fluidized bed data at the respective superficial gas velocities. Since the flow rates between the empty reactor and fluidized bed tests do not match exactly, a linear interpolation method is employed to calculate the empty bed pressures corresponding to the fluidized bed flow rates. Finally, the bed pressure drop is plotted as a function of superficial gas velocity and the minimum fluidization velocity is defined as the point in which the pressure drop across the bed remains constant. To determine the value of the minimum fluidization velocity, a point located around the knee of the plot (Figure 2) is identified as a reference point; then two linear trend lines are plotted using the reference point and 10 data points above and 10 data points below the reference point. The minimum fluidization velocity is then identified as the point where the two trend lines intersect. Figure 2 shows a sample plot obtained for glass beads where the static bed height corresponds to H/D = 1 without any acoustic field influence.

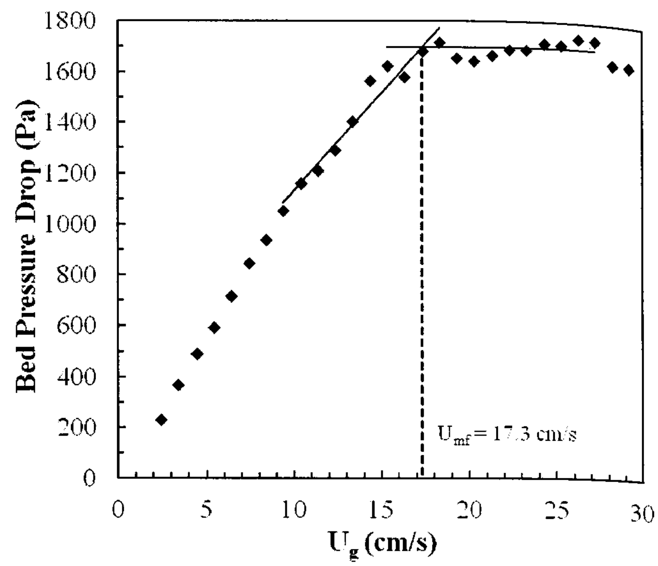

FIGURE 2: SAMPLE MINIMUM FLUIDIZATION PLOT FOR GLASS BEADS WITH H/D = 1 (NO ACOUSTIC FIELD WAS APPLIED).

RESULTS AND DISCUSSION

Effect of Frequency on the Minimum Fluidization Velocity.

Figure 3 shows the bed pressure drop as a function of superficial gas velocity for 500-600 μm glass beads at H/D = 0.5. Bed pressure drop increases as frequency increases, until it reaches a certain frequency, specifically 150 Hz, after this frequency, the bed pressure drop decreases with a further increase in frequency.

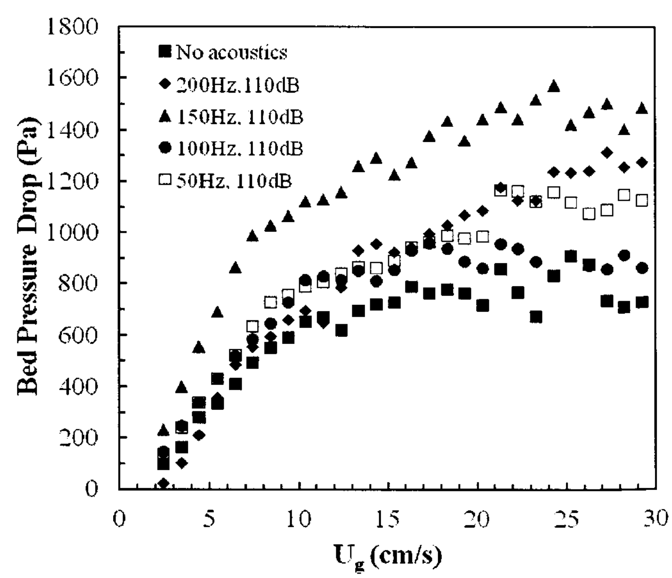

FIGURE 3: BED PRESSURE DROP AS A FUNCTION OF SUPERFICIAL GAS VELOCITY FOR 500-600 μm GLASS BEADS AT H/D = 0.5.

Minimum fluidization velocity, on the other hand, showed a significant change when frequency increased. As shown in Figure 4, the minimum fluidization decreased until it reached 150 Hz, where a minimum value is attained, after this frequency the minimum fluidization velocity increases again. This phenomenon is repeated for each size range tested, which indicates that the effect of frequency is independent of material size over the range 212-600 μm. The values of the minimum fluidization velocity presented in Figure 4 are the average of the 10 tests completed for each size range, and the error bars shown in Figure 4 represent one standard deviation of the average values. The value of the standard deviation for each of the size ranges varies between 0.2 – 0.23, which represents approximately 1-2% of the U_{mf}. Thus, Figure 4 clearly showed that there is a change in the minimum fluidization velocity due to a change in the frequency.

Similar results were found by Guo et al. [10] and Russo et al. [15]. Both studies revealed the same trends shown in Figure 4 – a reduction in the U_{mf} value until a certain frequency, and then an increase in the minimum fluidization. The difference between the results found in the literature and those of this study is the frequency value at which a minimum U_{mf} is observed, this difference between frequencies is hypothesized to be due to the natural frequencies of the respective gas – solid fluidized beds.

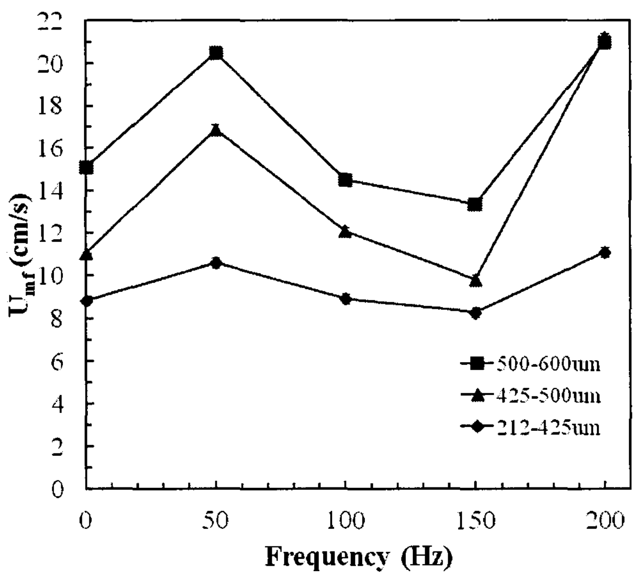

FIGURE 4: MINIMUM FLUIDIZATION VELOCITY AS A FUNCTION OF FREQUENCY FOR GLASS BEADS AT H/D = 0.5.

The fluidization index is defined as the bed pressure drop divided by the hydrostatic pressure created by the weight of the bed. Figure 5 and 6 show the fluidization index as a function of the superficial gas velocity for different sizes of glass beads and different H/D ratios. The sharp "knee" in each plot correlates to U_{mf} and these plots offer a clear picture of the effect of frequency on the minimum fluidization velocity. As frequency increases, less superficial gas velocity is needed to achieve material fluidization.

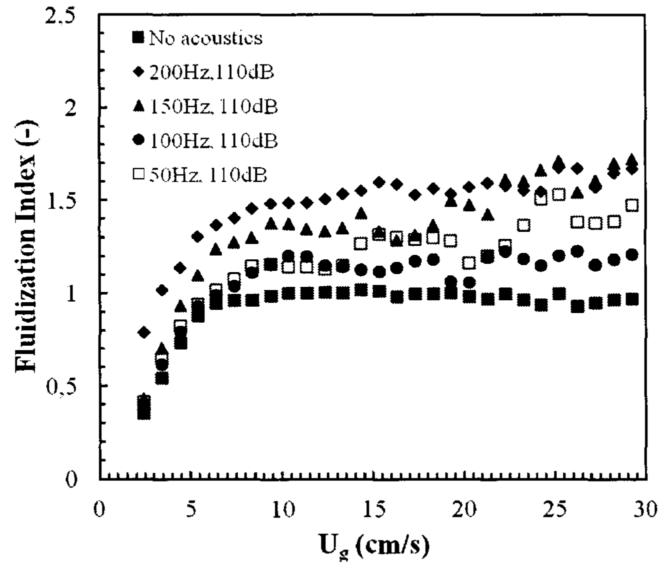

FIGURE 5: FLUIDIZATION INDEX AS A FUNCTION OF SUPERFICIAL GAS VELOCITY FOR GLASS BEADS 212-425 μm AT H/D = 0.5.

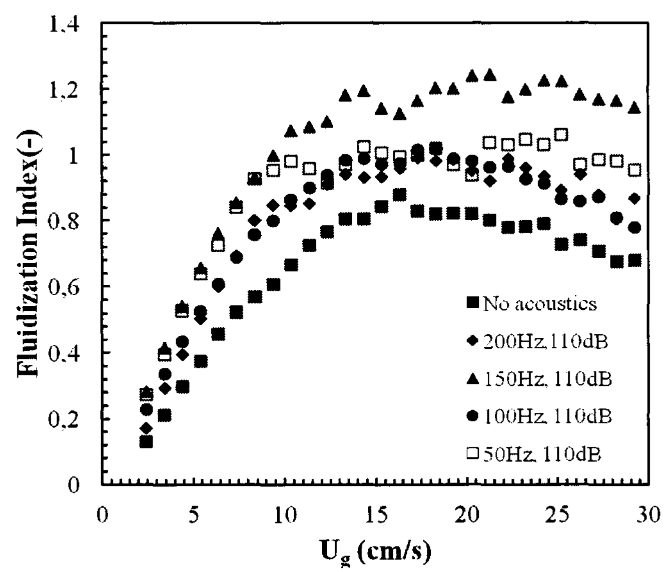

FIGURE 6: FLUIDIZATION INDEX AS A FUNCTION OF SUPERFICIAL GAS VELOCITY FOR GLASS BEADS 500-600 μm AT H/D = 1.

Effect of Bed Height on the Minimum Fluidization Velocity.

As was stated in the introduction, several studies in the literature have concluded that minimum fluidization velocity for a particular material is independent of bed height. However, when an acoustic field is applied to the fluidized bed, the independence between U_{mf} and bed height is not observed.

Figure 7 shows the minimum fluidization velocity as a function of bed height for a bed of 500-600 μm glass beads at different frequencies. As Figure 7 shows, the minimum fluidization velocity exhibits a change as the H/D ratio changes. This phenomenon is observed for each of the frequency conditions tested. For 50 Hz and 200 Hz, the change in U_{mf} is more drastic between H/D ratios, meanwhile between 100-150 Hz, there is a change but it is not as dramatic as the one observed for the other frequencies. This shows again that the optimal frequency in which the bed achieves a better and more homogeneous fluidization is located between these ranges of frequencies.

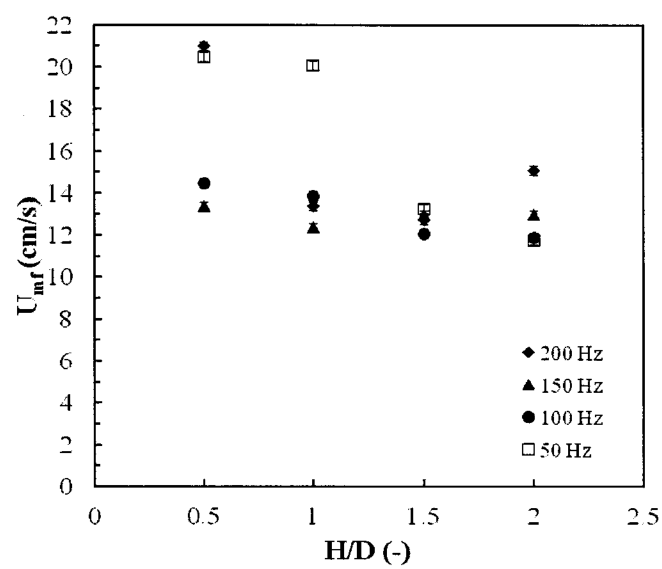

FIGURE 7: MINIMUM FLUIDIZATION VELOCITY AS A FUNCTION OF BED HEIGHT FOR 500-600 μm GLASS BEADS.

Figure 8 shows that fluidization is achieved with less superficial gas velocity between 100 and 150 Hz for all H/D ratios except H/D = 2. At H/D = 2, U_{mf} is lowest between 50 and 100 Hz, which implies that as the surface of the bed approaches the acoustic source, lower frequencies are able to fluidized the material and reach homogeneous fluidization without the need of increasing the acoustic frequency.

Leu et al. [9] and Russo et al. [15] proved that as the weight of the bed changed in a sound-assisted fluidized bed, the minimum fluidization velocity over the entire frequency range of their studies changed (Figure 7). Also, they showed that the change in the bed weight does not influence the trend exhibited by the minimum fluidization velocity as a function of frequency, and their results showed similar trends as the ones shown in Figure 8. The possible explanation for this behavior is that the increase in the sound attenuation due to the larger amount of solids decreases the average SPL under which beds of different weights are operated [15].

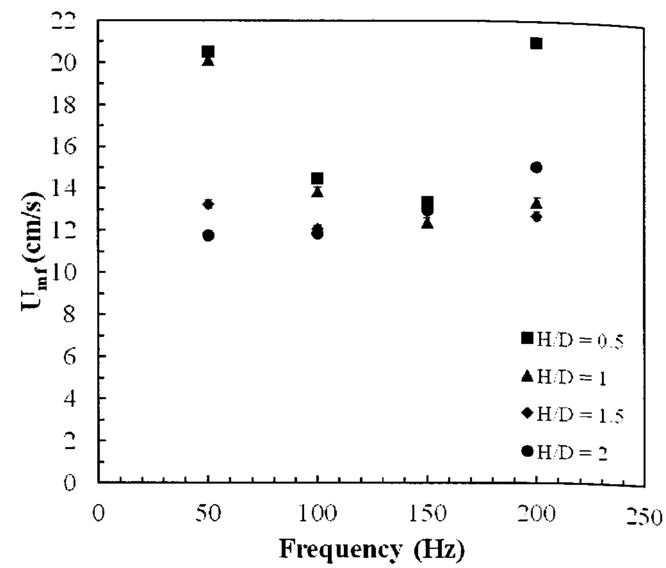

FIGURE 8: MINIMUM FLUIDIZATION VELOCITY AS A FUNCTION OF FREQUENCY FOR 500-600 μm GLASS BEADS AT DIFFERENT BED HEIGHTS.

CONCLUSIONS

The presence of an acoustic field in a fluidized bed filled with glass beads at different bed heights improved the ease of material fluidization (i.e., lower U_{mf}) in every size range studied.

Minimum fluidization velocity decreased with an increase in acoustic frequency until the material reached a point of homogeneous fluidization, beyond that point, U_{mf} started to increase. The results obtained in this research corroborate previous studies found in the literature.

Fluidized beds enhanced with acoustic sources exhibit dependence between bed height and minimum fluidization velocity. As H/D increases, and the frequency is fixed, there are changes in the minimum fluidization velocity, these changes did not happen when there was no acoustic field present in the bed material.

Moreover, as the bed surface moves closer to the acoustic source, the frequency of the sound needed to achieve a homogeneous fluidization is less than the one needed when the bed surface is farther from the sound source.

Future studies will address the effects of acoustic frequency and sound pressure level on fluidized beds fill with different materials.

ACKNOWLEDGMENTS

This work was supported through Iowa State University.

REFERENCES

[1] Ramos Caicedo, G., García Ruiz, M., Prieto Marqués, J. J. and Guardiola Soler, J. (2002). "Minimum fluidization velocities for gas-solid 2D beds." *Chemical Engineering and Processing,* **41**(9): 761-764.

[2] Zhong, W., Jin, B., Zhang, Y., Wang, X. and Xiao, R. (2008). "Fluidization of biomass particles in a gas–solid fluidized bed." *Energy & Fuels,* **22**(6): 4170-4176.

[3] Sau, D. C., Mohanty, S. and Biswal, K. C. (2007). "Minimum fluidization velocities and maximum bed pressure drops for gas-solid tapered fluidized beds." *Chemical Engineering Journal,* **132**(1-3): 151-157.

[4] Hilal, N., Ghannam, M. T. and Anabtawi, M. Z. (2001). "Effect of bed diameter, distributor and inserts on minimum fluidization velocity." *Chemical Engineering and Technology,* **24**(2): 161-165.

[5] Zhong, W., Chen, X. and Zhang, M. (2006). "Hydrodynamic characteristics of spout-fluid bed: Pressure drop and minimum spouting/spout-fluidizing velocity." *Chemical Engineering Journal,* **118**(1-2): 37-46.

[6] Gunn, D. J. and Hilal, N. (1997). "The expansion of gas-fluidised beds in bubbling fluidisation." *Chemical Engineering Science,* **52**(16): 2811-2822.

[7] Cranfield, R. R. and Geldart, D. (1974). "Large particle fluidisation." *Chemical Engineering Science,* **29**(4): 935-947.

[8] Escudero, D. and Heindel, T. J. (2011). "Bed height and material density effects on fluidized bed hydrodynamics." *Chemical Engineering Science*, **66**(16): 3648-3655.

[9] Leu, L. P., Li, J. T. and Chen, C. M. (1997). "Fluidization of group B particles in an acoustic field." *Powder Technology,* **94**(1): 23-28.

[10] Guo, Q., Liu, H., Shen, W., Yan, X. and Jia, R. (2006). "Influence of sound wave characteristics on fluidization behaviors of ultrafine particles." *Chemical Engineering Journal.* **119**(1): 1-9.

[11] Kaliyaperumal, S., Barghi, S., Zhu, J., Briens, L. and Rohani, S. (2011). "Effects of acoustic vibration on nano and sub-micron powders fluidization." *Powder Technology,* **210**(2): 143-149.

[12] Levy, E. K., Shnitzer, I., Masaki, T. and Salmento J. (1997). "Effect of an acoustic field on bubbling in a gas fluidized bed." *Powder Technology,* **90**(1): 53-57.

[13] Guo, Q., Zhang, J. and Hao, J. (2011). "Flow characteristics in an acoustic bubbling fluidized bed at high temperature." *Chemical Engineering and Processing: Process Intensification,* **50**(3): 331-337.

[14] Si, C. and Guo, Q. (2008). "Fluidization characteristics of binary mixtures of biomass and sand quartz in an acoustic fluidized bed." *Industrial and Engineering Chemistry Research*, **47**(23): 9773-9782.

[15] Russo, P., Chirone, R., Massimilla, L. and Russo, S. (1995). "The influence of the frequency of acoustic waves on sound-assisted fluidization of beds of fine particles." *Powder Technology*, **82**(1): 219-230.